Green Quantum Computing in the Sky

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***Abstract*—The cryogenic cooling requirements of quantum computing pose significant challenges to sustainable deployment. We propose deploying quantum processors on stratospheric High Altitude Platforms (HAPs), leveraging $-50°\mathrm{C}$ ambient temperatures to reduce cooling demands by 21%. Our analysis demonstrates that quantum-enabled HAPs support 30% more qubits than terrestrial quantum data centers while maintaining superior reliability, especially when leveraging advanced hardware capabilities. By leveraging strategic atmospheric positioning, this solar-powered solution enables sustainable, high-performance quantum computing.**

I. Introduction

Quantum computing represents a revolutionary paradigm that harnesses quantum mechanical principles. In this paradigm, qubits replace bits as the fundamental data unit, enabling advanced parallel computation and significantly increased storage capacity [1]. This potential has made quantum computing essential for solving previously intractable problems in areas like finance, cryptography, and chemical engineering, while also empowering next-generation wireless networks. Consequently, it has evolved into a strategic technology in both academia and industry [2]–[5].

However, these computational advantages come at a cost: quantum data centers (QDCs) consume enormous amounts of energy [6], [7]. For instance, a QDC may complete a task twice as fast as a traditional one but consume ten times more energy due to its stringent cryogenic cooling requirements [7]. Most quantum computing systems must operate at extremely low temperatures, from several mK to $10K$, to maintain qubit states and prevent errors caused by thermal noise and vibrations [2]. Consequently, the thermodynamic aspects of QDCs require thorough investigation to reduce cooling energy consumption. Prominent cooling techniques for quantum chips in data centers include dilution refrigeration, pulse tube refrigeration, and laser cooling. More advanced technologies are gaining momentum, such as immersing quantum circuits in Helium 3 liquid and using the magnetocaloric effect of supersolids. However, achieving and maintaining cryogenic environments for qubits still demands substantial energy and expense and pose a serious impediment to quantum computing adoption [8], [9]. Thus, innovative engineering approaches are needed to enable high-performance quantum computing while ensuring environmental sustainability.

We propose a Quantum Computing-Enabled High Altitude Platform (QC-HAP) to address this energy challenge. As shown in Figure 1, the QC-HAP hosts quantum processors aboard a stratospheric platform (17-20 km altitude) [10]. The quantum devices are enclosed in cryostats to maintain the required cryogenic temperature. While cryostats are still needed, the naturally low ambient temperatures $-50°\mathrm{C}$ and $-15°\mathrm{C}$ drastically reduce the thermal gradient, thereby slashing the energy required for cryogenic cooling compared to terrestrial facilities. The HAP is powered sustainably via solar energy harvested during the day and stored in Lithium-Sulfur batteries for nighttime operation [10], [11]. We highlight that the solar panels weight is not included in the HAP payload in lift calculations as it is part of the HAP's structural mass. Moreover, the harvested solar power is not used to lift the HAP, but it covers the payload power and the propulsion power needed to maintain its quasi-stationarity.

From a communication perspective, HAPs connect to terrestrial QDCs through free-space optical (FSO) links, ensuring broadband data access [12]. To address the signal attenuation and decoherence over long distances, repeaters are deployed on low altitude platforms (LAP) to maintain the seamless connectivity between HAPs and satellites, as depicted in Figure 1. This integration of quantum communication with non-terrestrial networks aligns with the sixth-generation (6G) ecosystem goals and promotes non-terrestrial networks as a key enabler for quantum systems, where fiber optics ensure the connection of QDCs in the terrestrial segment while FSO enables communication in the aerial and space segments [13], [14]. The QC-HAP offers significant strategic advantages. Its flexible deployment allows it to be repositioned over demand hotspots or remote regions, dynamically extending quantum computing coverage and alleviating computational bottlenecks. This mobility also minimizes latency compared to fixed, remote terrestrial locations, enhancing Quality of Service.

In this work, we analyze the QC-HAP from energy efficiency and computational performance perspectives. Our main contributions are:

- We introduce a novel framework for green, flexibly-deployed quantum computing in the stratosphere and demonstrate its superior energetic and computational performance over conventional terrestrial data centers.
- We conduct a comprehensive analysis of the trade-off between the energy and computational advantages of QC-HAP, providing practical insights for real-world operation under environmental constraints.
- We investigate the scalability of QC-HAP to mitigate

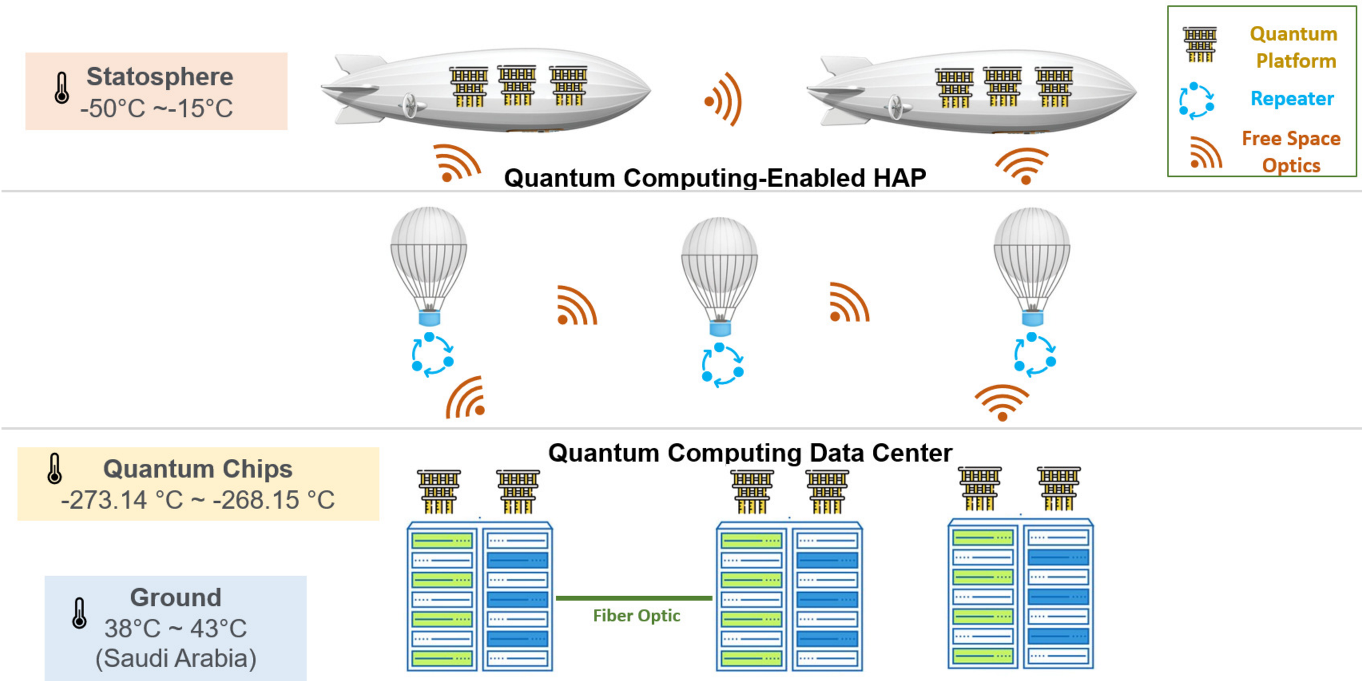

Fig. 1. System architecture of the proposed Quantum Computing-Enabled High Altitude Platform (QC-HAP). Quantum processors are housed in a stratospheric HAP, which connects to terrestrial data centers and satellites via free-space optical (FSO) links, with Low Altitude Platforms (LAPs) acting as quantum repeaters to mitigate signal loss.

current quantum hardware limitations and pinpoint the key quantum communication challenges that must be addressed.

While our study remains independent of any specific quantum technology due to rapid advancements in this emerging field, we consider two leading qubit architectures: superconducting qubits and ion trap qubits. These platforms were selected for their maturity, stability, and distinct characteristics in terms of scalability and coherence time [7]. All simulations are conducted by using MATLAB, based on the realistic parameters summarized in Table I, and executed by an Intel Core i7 CPU [15], [16].

TABLE I
SIMULATION SETTINGS

Type	Parameter	Numerical Value
Quantum Properties Inputs	Temperature in the Ion trap cryostat	4.5 K
	Temperature in the Superconducting cryostat	15 mK
	Carnot efficiency of cryogenic cooling system	0.15
	Cryostat heat transfer coefficient	0.3 W/m^2K
	Cryostat geometric constant	6
HAP Inputs	Maximum Payload	450 kg
	Area of the Photovoltaic (PV) Surface	8000 m^2
	Efficiency of the PV	0.4
	Propeller efficiency	0.8
	Battery capacity	2 kWh/kg

II. ENERGY ADVANTAGE

While QDCs are often claimed to be more energy-efficient than traditional data centers due to their faster processing, comprehensive models are needed to evaluate the energy efficiency of QDCs by accounting for major influencing factors including quantum thermodynamics, quantum physics, information science [6]–[8], [17]. We adopt the analytical model proposed in [16], which evaluates both energy effectiveness and computational performance of QDCs independently of hardware architecture and quantum algorithms. In this section, we examine the energy savings achieved by our quantum platform and analyze its key factors.

A. *Qubit's Properties Impact*

QC-HAP can reduce energy consumption by leveraging the lower stratospheric temperatures, requiring less cooling energy compared to QDCs. However, this energy reduction varies with qubit architecture, as each type operates within different cryogenic temperature range. Ion trap qubits utilize electromagnetic fields to confine ions within a specific region and must operate at temperatures around 4K to control precisely their quantum states [16], [18]. In contrast, superconducting qubits employ electrical circuits with superconducting materials and Josephson junctions, which requires extremely low temperatures (10-20 mK), where quantum effects dominate thermal effects [7], [16], [18]. The energy savings achieved by the stratospheric quantum system also depend on the data center's architecture. Quantum systems comprise components operating at both cryogenic temperatures (for qubit measurement and readout) and ambient temperatures (for sending data to classical data centers for processing) [7], [16].

To validate our assertions, we analyze the power usage effectiveness (PUE) of QC-HAP. PUE is a standard key

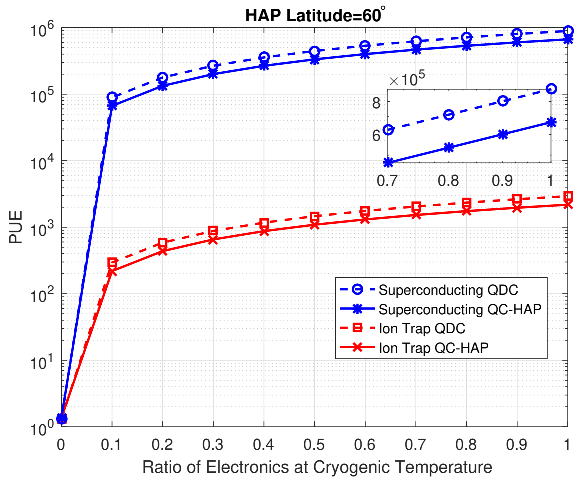

Fig. 2. Power Usage Effectiveness (PUE) comparison between conventional Quantum Data Centers (QDCs) and the QC-HAP for different qubit architectures and cryogenic circuit ratios. The QC-HAP consistently demonstrates superior energy efficiency, with ion trap qubits outperforming superconducting ones.

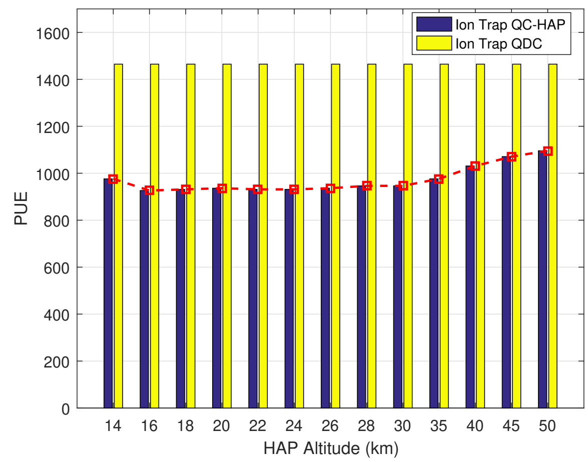

Fig. 3. Power Usage Effectiveness (PUE) of the QC-HAP as a function of altitude. The QC-HAP achieves optimal energy efficiency at approximately 20 km, reducing energy consumption by 21% compared to a QDC.

performance indicator for data center energy efficiency that measures the ratio of the total data center power consumption to computing power. The PUE of QDCs is given by [16]:

$$PUE|_{\mathrm{QDC}} = 1 + \frac{\phi(1+\beta\, n_p^{-1/3})(T_o - T_c)}{\eta_C^2\, T_c} + (1-\phi)(1 - PUE_{\mathrm{DC}}); \tag{1}$$

where ϕ is the ratio of power use between cryogenic and non-cryogenic electronics, β is the ratio of cryostat external heat transfer to internal power dissipation, n_p is the number of qubits, η_C is the Carnot efficiency achieved by cryogenic cooling system, T_c is the operating temperature in the cryostat, T_o is the ambient temperature, PUE_{DC} is the power usage effectiveness of conventional data centers (that doesn't implement quantum servers). Figure 2 quantifies the energy advantage of stratospheric deployment across different qubit architectures. The results demonstrate firstly that this aerial quantum solution is more energy efficient since it consistently achieves lower PUE than QDC across different qubit types and cryogenic circuit ratios. This efficiency gain stems directly from the reduced temperature differential, where stratospheric temperatures decrease the cooling power requirements by nearly an order of magnitude. Secondly, QC-HAP with ion trap qubits demonstrate significantly better PUE compared to those with superconducting qubits, due to higher thermal efficiency and optimized energy usage.

B. HAP's Properties Impact

We note that the ambient temperature in the stratosphere is variable and depends mainly on the altitude, decreasing around 20 km but rises above 30 km [19]. The results in Figure 3 show that QC-HAP consistently achieves lower PUE compared to QDCs across various altitudes, with optimal energy efficiency at approximately 20 km. At this optimal altitude, our proposed system can reduce energy consumption by 21% compared to QDCs.

C. Weather Conditions Impact

Weather conditions impact the energy efficiency of our quantum platform significantly because they affect directly the harvested solar power, which constitute the main source of energy supply for our proposed system. Solar irradiance in the stratosphere is largely unaffected by cloud, precipitation or snow because these meteorological phenomena are restricted to the troposphere [20]. However, solar irradiance in the stratosphere is subject to seasonal variations. Figure 4 reveals the impact of seasonal changes on the PUE of QC-HAP. We notice a significant variation across the different days of the year for a given HAP latitude. The stratospheric quantum system is more energy-efficient during the summertime (day numbers between 150 and 200) in the northern hemisphere for the latitudes around 20° and 40° thanks to longer daylight hours. Hence, more solar power can be harvested. We observe that we have the opposite trend in southern hemisphere because this same period corresponds to winter. Therefore, the temporal and geographical parameters of HAP deployment should be well investigated to optimize the energy efficiency of QC-HAP.

III. Computational Advantage

The computational performance of QDCs should be based on a comprehensive assessment that takes into account multiple influencing factors beyond solving complex problems at significantly accelerated speeds [1], [16]. Currently, no universally-adopted model is reported in the literature, even though IBM uses practically the quantum volume (QV) metric that is based on the number of qubits, the circuit depth and gate fidelity [16]. In this section, we investigate the computational performance of our aerial quantum solution by evaluating the interplay between the supported number of qubits and the resulting reliability.

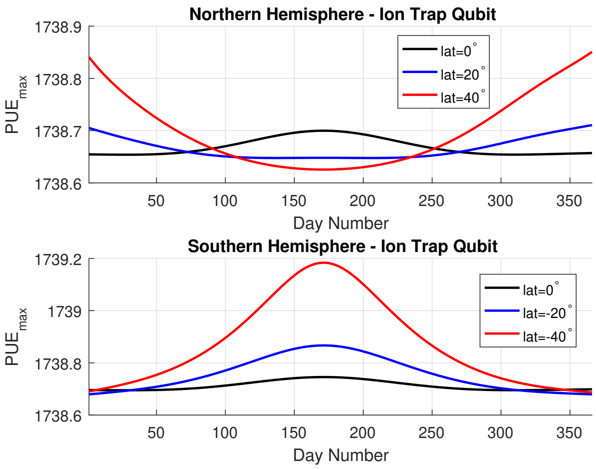

Fig. 4. Impact of seasonal variations on QC-HAP energy efficiency (PUE) across different latitudes. Efficiency is highest during summer months in each hemisphere due to longer daylight hours and greater solar energy harvest, underscoring the importance of strategic deployment timing and location.

A. Number of Qubits

The number of qubits is a crucial parameter to evaluate the computational performance of QDCs because it determines the supported number of quantum states and dictates the size of the problems that can be solved in QDCs. Accordingly, increasing the number of qubits is necessary for QDCs to surpass classical data center computationally. However, increasing the number of qubits leads to additional consumed energy and undermines the energy advantage. Therefore, we investigate whether our quantum platform can achieve the computational advantage while controlling the energy consumption.

We underline that the supported number of qubits in the QC-HAP would depend also on HAP properties since the quantum payload power is limited by the harvested solar power and the propulsion power [10]. Specifically, the quantum payload power in our stratospheric quantum system is the total power $P_{\text{T}}|_{\text{QC}-\text{HAP}}$ consumed by the quantum chips over computation and cooling in the HAP. It is given by $P_{\text{T}}|_{\text{QC}-\text{HAP}}(n_p) = q\ P^{*}_{\text{T}}|_{\text{QC}-\text{HAP}}(n_p)$; where q is the computational power consumed by one qubit, n_p is the number of qubits and $P^{*}_{\text{T}}|_{\text{QC}-\text{HAP}}(n_p)$ is the scaling power of the QC-HAP given by:

$$P^{*}_{\text{T}}|_{\text{QC}-\text{HAP}}(n_p) = V_{\text{Q}}(n_p)^{\frac{1}{6}} \frac{\phi\, \beta\, (T_o - T_c)}{\eta_C^2\, T_c} + V_{\text{Q}}(n_p)^{\frac{1}{2}} \left(1 + \frac{\phi(T_o - T_c)}{\eta_C^2\, T_c} + (1-\phi)(1 - PUE_{\text{DC}-\text{HAP}})\right); \tag{2}$$

where ϕ is the ratio of power use between cryogenic and non-cryogenic electronics, β is the ratio of cryostat external heat transfer to internal power dissipation, η_C is the Carnot efficiency achieved by cryogenic cooling system, T_c is the operating temperature in the cryostat, T_o is the ambient temperature, PUE_{DC-HAP} is the power usage effectiveness of HAP-enabled-data centers and V_{Q} is the quantum volume. Therefore, we updated the analytical model of the scaling power needs provided in [16] to include the HAP parameters while considering the HAP flying condition as follows [10]:

$$\begin{aligned} P_{\text{T}}|_{\text{QC}-\text{HAP}}(n_p) &= P^{\text{payload}}_{\text{HAP}}(l, d, \mathcal{A}_{\text{pv}}, \eta_{\text{pv}}, \eta_{\text{prop}}) \\ &= \eta_{\text{pv}}\, \mathcal{A}_{\text{pv}}\, G(l,d) - \frac{\rho_{\text{air}}}{2\eta_{\text{prop}}}\, v^3_{\text{wind}}(l,d)\, v^{2/3}_{\text{HAP}}\, C_{\text{D}}; \end{aligned} \tag{3}$$

where l is the HAP latitude, d is the day number in the year, η_{pv} is the efficiency of the photo-voltaic system, $\mathcal{A}_{\text{pv}}$ is the area of the photo-voltaic system, $G(l,d)$ is the total extra-terrestrial solar radiance per m^2, ρ_{air} is the air density, η_{prop} is the propeller efficiency, v_{wind} is the wind velocity, v_{HAP} is the HAP velocity C_{D} is the drag coefficient.

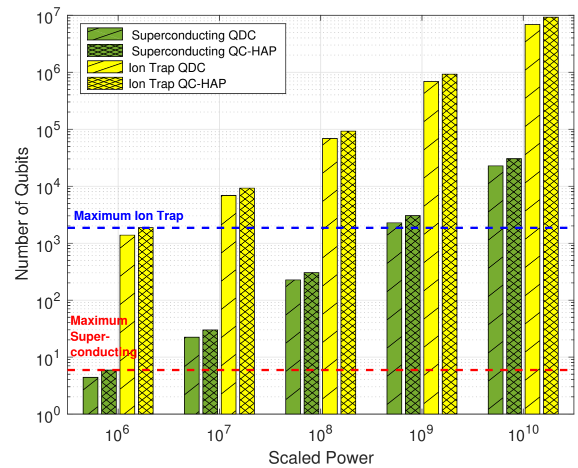

Fig. 5. The number of supported qubits scales with the supplied power for both conventional QDCs and the QC-HAP. The QC-HAP supports at least 30% more qubits for the same energy input. Dashed lines represent the operational limits imposed by the HAP's energy harvesting capacity.

The scalability advantages become evident in Figure 5, where the logarithmic relationship between power and qubit count reveals QC-HAP's superior computational density. Our proposed system improves the number of supported qubits compared to QDC by at least 30% with the same supplied energy. Moreover, the ion trap architecture is more energy-efficient since it offers significantly higher number of qubits for the same consumed energy either for QDC or QC-HAP. As more energy is supplied to both quantum systems, more qubits can be processed.

However, HAP has limited harvested energy determined by the surface of the photovoltaic solar panels; which reaches 8000 m^2 in our study. The harvested energy limitation sets a threshold on the supported number of qubits illustrated through the red and blue dashed lines in Figure 5. We notice that the outperformance of the QC-HAP over QDC can be sustained only for the lowest supplied scaled power around 10^6. Therefore, the solar panels surface must be increased to harvest the required energy that guarantees the computational advantage for our aerial quantum solution. One way to achieve this goal is the deployment of a constellation of HAPs that host QDCs.

B. *Effective Error Rate*

The computational advantage of QDCs does not only rely on the supported number of qubits, but also it depends on qubits' fidelity assessed through the effective error rate ϵ_{eff}. Interestingly, the effective error rate is also correlated to the number of qubits in the quantum system and is affected in two distinct ways by its variation given the expression of the quantum volume [16]:

$$V_{\text{Q}}(n_p) = \max_{n \leqslant n_p} \left(\min \left[n, \frac{1}{n\ \epsilon_{\text{eff}}} \right]^2 \right) \tag{4}$$

On the one hand, increasing the number of qubits rises thermal noise besides interference and deteriorates reliability. That's why, current quantum systems operate with limited number of qubits [21]. On the other hand, increasing the number of qubits can be beneficial for reliability since the added qubits can serve as redundancy qubits used for error detection and/or correction. Specifically, a peak number of qubits can be supported to reach the optimal computational performance. Below this peak, errors can be controlled by implementing the necessary fault tolerance mechanisms. Beyond this peak, the qubits' quality is compromised without any processing improvement. Therefore, we examine the interplay between scalability and reliability in QC-HAP while considering the HAP energetic constraints; where the reliability of QC-HAP is assessed through the effective error rate given by:

$$\epsilon_{\text{eff}}\Big|_{\text{QC-HAP}} = \tag{5}$$

$$\left(\left(\frac{P_{\text{T}}|_{\text{QC-HAP}}}{2q\alpha} + \sqrt{\left(\frac{P_{\text{T}}|_{\text{QC-HAP}}}{2q\alpha} \right)^2 + \left(\frac{\gamma}{3\alpha} \right)^3} \right)^{-1/3} + \left(\frac{P_{\text{T}}|_{\text{QC-HAP}}}{2q\alpha} - \sqrt{\left(\frac{P_{\text{T}}|_{\text{QC-HAP}}}{2q\alpha} \right)^2 + \left(\frac{\gamma}{3\alpha} \right)^3} \right)^{-1/3} \right)^{-1/3};$$

where $\alpha = \left(1 + \frac{\phi (T_o - T_c)}{\eta_C^2\ T_c} + (1-\phi)(1 - PUE_{\text{DC-HAP}}) \right)$, such that $PUE_{\text{DC-HAP}}$ is the power usage effectiveness of a data center-enabled HAP and $\gamma = \frac{\phi\ \beta\ (T_o - T_c)}{\eta_C^2\ T_c}$, such that T_o is the ambient temperature in the HAP.

Figure 6 provides evidence that our proposed system offers better qubits' fidelity since it has lower effective error rates. We also observe that the ion trap architecture is more reliable than the superconducting architecture for both quantum systems. Interestingly, the error rate improves when more power is supplied to the quantum system because more qubits can be supported (cf. Figure 5). This is due to the fact that these simulations are conducted below the peak number of supported qubits. Therefore, the qubits introduced into the QDCs are used by fault tolerance mechanisms to correct errors; which enhances the effective error rate. When the HAP's energetic constraints are considered (red and blue dashed lines in Figure 6), the outperformance of the QC-HAP over QDCs can be sustained only for the lowest supplied scaled power around 10^6. We note that the rates achieved are far below the actual values measured in deployed quantum systems; which are around 10^{-4} and 10^{-3} [16]; which incites quantum's hardware development.

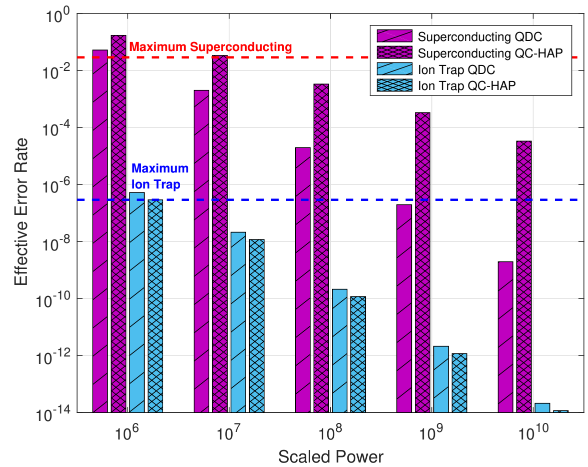

Fig. 6. Effective error rate as a function of supplied power for different quantum architectures. The QC-HAP achieves a lower error rate (higher reliability) than QDCs for the same power input. The ion trap architecture demonstrates superior reliability over superconducting qubits. Dashed lines indicate the HAP's operational energy constraint.

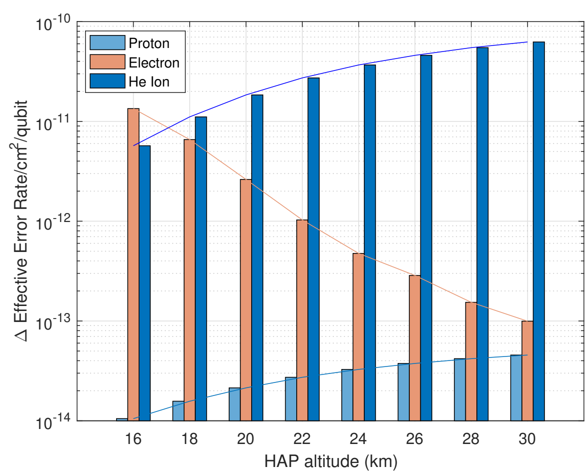

Fig. 7. Impact of cosmic rays (protons, electrons, helium ions) on the effective error rate of the QC-HAP across altitudes. The degradation in reliability is negligible (difference $< 10^{-10}$), demonstrating that cosmic radiation does not negate the QC-HAP's performance advantage over terrestrial alternatives.

C. *Cosmic Rays Considerations*

When a cosmic ray hits a quantum chip, it injects energy into the quantum chip and generates photons or quasi-particles that might yield correlated errors. Therefore, it is crucial to study the impact of cosmic rays on the energy/reliability performance of the stratospheric quantum system; particularly since quasi-particle flux is significantly higher in the stratosphere compared to sea level altitudes. Specifically, we address the power overhead required for cooling after the quasi-particles hits. The cooling power overhead is necessary to remove thermal heat deposited and depends on the cooling efficiency of the cryogenic system, the flux of the quasi-particles, their stopping powers and the quantum chip area and material and can be estimated as follows [16]:

$$P_{\text{cool}}^{\text{overhead}} = \eta_C \, \frac{T_c}{T_c - T_o} \, P_{\text{deposit}}; \tag{6}$$

where P_{deposit} is the power deposited per hit and it is given by [22]:

$$P_{\text{deposit}} = \Phi(h) \; \mathcal{A}_{chip} \; E_{\text{deposit}}; \tag{7}$$

such that $\Phi(h)$ is the flux of quasi-particles at altitude h, $\mathcal{A}_{chip}$ is the quantum chip area and E_{deposit} is the energy deposited per hit and it is given by [23]:

$$E_{\text{deposit}} = \rho_{material} \; \delta \; \frac{dE}{dx}; \tag{8}$$

such that $\rho_{material}$ is the density of the quantum chip material, δ is the quantum chip thickness and $\frac{dE}{dx}$ is the stopping power and it quantifies the energy loss per unit mass thickness of the material traversed by the quasi-particle.

While considering the cooling overhead in the power budget of our quantum platform, we re-evaluate the effective error rate of QC-HAP under cosmic rays impact for different quasi-particles namely protons, electrons and Helium ions. Accordingly, the effective error rate of the QC-HAP under the impact of cosmic rays is given by:

$$\epsilon_{\text{eff}}\Big|_{\text{QC}-\text{HAP}}^{\text{cosmic}} = \left(\sqrt[3]{\frac{P_{\text{T}}^{\text{cosmic}}}{2\,q\,\alpha} + \sqrt{\left(\frac{P_{\text{T}}^{\text{cosmic}}}{2\,q\,\alpha}\right)^2 + \left(\frac{\gamma}{3\alpha}\right)^3}} \right. \\ \left. + \sqrt[3]{\frac{P_{\text{T}}^{\text{cosmic}}}{2\,q\,\alpha} - \sqrt{\left(\frac{P_{\text{T}}^{\text{cosmic}}}{2\,q\,\alpha}\right)^2 + \left(\frac{\gamma}{3\alpha}\right)^3}} \right)^{-\frac{1}{3}}; \tag{9}$$

where,

$$P_{\text{T}}^{\text{cosmic}} = P_{\text{T}}(l, d, \mathcal{A}_{\text{pv}}, \eta_{\text{pv}}, \eta_{\text{prop}}) \\ - \eta_C \, \frac{T_c}{T_c - T_o} \, \Phi(h) \; \mathcal{A}_{chip} \; \rho_{material} \; \delta \; \frac{dE}{dx}; \tag{10}$$

Then, we compare the obtained rates with and without cosmic rays impact across different HAP altitudes. The numerical values of the quasi-particle flux as function of altitudes were obtained by using EXcel-based Program for calculating Atmospheric Cosmic-ray Spectrum (EXPACS), which is an implementation of the models of [24]. The values of the stopping powers were derived by interpolating the kinetic energy outputs from EXPACS into the PSTAR, ESTAR and ASTAR databases provided by NIST [25]–[27].

Figure 7 addresses a key concern for stratospheric deployment: cosmic radiation exposure. Despite particle flux increasing 100-fold at operational altitudes, the induced error rates remain negligible. Helium ions—the most impactful particles—contribute only 10^{-10} additional errors per cm² per qubit at 20 km altitude, validating that cosmic rays do not compromise QC-HAP's reliability advantage established in Figure 6).

IV. Scalability Prospects

The scalability of QDCs is of paramount importance to enable the execution of complex quantum tasks [28], [29]. However, increasing the number of qubits complicates their control/measurement and deteriorates their quality when the peak number of supported qubits is exceeded [28], [29]. Therefore, it is crucial to scale QDCs without compromising their reliability. The concept of distributed quantum computing was introduced with this purpose by interconnecting multiple quantum systems via quantum communications to execute quantum tasks collaboratively and efficiently [21], [28]. By leveraging this concept, we propose the Quantum Computing-Enabled Multi-HAPs (QC-Multi-HAPs) to address the previously discussed computational issues. Specifically, a constellation of HAPs is deployed in the sky where each HAP hosts flying quantum servers and communicates with the other HAPs over quantum signals. In this section, we investigate whether QC-Multi-HAPs can solve the energy limitations encountered by QC-HAP. Then, we discuss the potential opportunities and the key challenges related to QC-Multi-HAPs mainly from a communication perspective.

A. Two-Dimensional Performance

It is crucial to study the performance of QC-Multi-HAPs from two perspectives: computational perspective and energy-usage perspective. To conduct this study, we opt for an ion trap architectures since its outperformance was proven over the superconducting architecture in the previous sections. Specifically, we monitor the supported number of qubits and the effective error rate for QC-Multi-HAPs while incrementing the HAPs number in the considered constellation. The energy consumption is controlled through the harvested energy by the solar panels deployed on the surfaces of the considered HAPs.

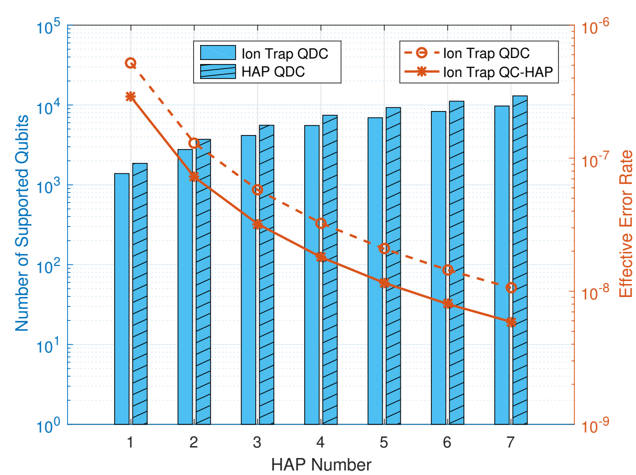

Fig. 8. Scalability of the multi-HAP constellation: (a) Supported number of qubits and (b) effective error rate improve as more HAPs are added. A multi-HAP system surpasses the performance of a single QDC, overcoming the energy limitations of a single platform.

Figure 8 demonstrates that scaling our HAP constellation improves the computation performance of our quantum platform in terms of peak number of qubits and reliability. Specifically, the number of supported qubits shows a continuous increase while the effective error rate remains in a downward trend. We observe also that QC-Multi-HAPs can achieve better results than QDC while consuming the same energy amounts. We conclude that deploying multiple quantum servers over different HAPs is a viable solution to scale QDCs without compromising their reliability and while conserving their energy advantage. However, we stress that such benefits are only guaranteed when a reliable communication with efficient connections is established between the flying quantum servers hosted in the constellation of HAPs. Therefore, different communication aspects must be explored carefully while focusing on the opportunities and challenges of quantum specificity.

B. Communication Considerations

Quantum communication is a pivotal enabler for QC-Multi-HAPs because qubits cannot be duplicated or cloned between different quantum systems due to the non-cloning quantum principle. Instead, entangled quantum states are transferred over quantum channels [28]. The main role of quantum channels is to preserve quantum properties such as superposition and entanglement. Currently, optical fiber and free-space optical signals are the best means to ensure these requirements. Typically, optical fibers are used over short distances unless some repeaters are deployed. However, FSO can be used over long distances because photons encounter less resistance in the air. Therefore, quantum communication between the adjacent flying QDCs should be leveraged through FSO thanks to the advantageous characteristics of the stratosphere. Specifically, the stratosphere is atmospherically stable since it is not affected by the turbulence caused by rains. Also, it has a lower air density and cloud density; which reduces scattering and absorption and undermines signal attenuation/blockage [30].

However, QC-HAP may exchange quantum information with remote HAPs or with terrestrial QDCs. Hence, the quantum signal must propagate over long distances or traverse the troposphere, which creates aggressive conditions for FSO transmission. One promising approach to overcome these challenges involves non-terrestrial network (NTN) integration [31]. Specifically, unmanned aerial vehicles (UAV)s, balloons and satellites can play the role of swarms of repeaters to transmit the quantum information collaboratively while conserving its properties and quality [30]. QC-Multi-HAPs is endorsed hence by a mesh network of repeaters spread over the space, air and ground segments that improve the quantum network resilience and expand its coverage [12], [29]. However, the repeaters' placement must be optimized to schedule the transfer of entanglement's states efficiently and reliably. In this way, quantum services can be provisioned dynamically from QC-Multi-HAPs at various times, locations, and weather conditions thanks to the flexible deployment of HAPs and LAPs and the global reach of satellites [30]. This provisioning should rely on adaptive resource allocation and efficient routing between repeaters and HAPs to take into account the different requirements of quantum applications [28].

Although NTN integration paves the way for large-scale quantum networks, QC-Multi-HAPs is not immune to errors and failures during information exchange. For instance, quantum decoherence can occur due to the distance traveled by the qubits between the HAPs or the repeaters or due to the interactions with light or interference with classical communications; which leads to the loss of quantum properties [29]. Therefore, quantum fault tolerance mechanisms should be applied while taking into account the supplementary qubits needed to manage the error detection/correction overheads.

V. Discussion and Future Directions

In this work, we have proposed and analyzed a Quantum Computing-Enabled High Altitude Platform (QC-HAP) as a sustainable and high-performance alternative to terrestrial QDCs. By leveraging the natural cryogenic environment of the stratosphere, the QC-HAP demonstrated superior energy efficiency, achieving a significantly lower Power Usage Effectiveness (PUE) and reducing cooling energy consumption by up to 21% compared to conventional ground-based systems. Computationally, the QC-HAP supported at least 30% more qubits for the same energy input and maintained a lower effective error rate, with ion trap architectures outperforming superconducting ones. Furthermore, we showed that the detrimental impact of cosmic ray on reliability is negligible, affirming the stratospheric viability of the platform. Finally, we proposed a scalable multi-HAP constellation architecture to overcome individual energy constraints and extend computational advantages. Despite these promising results, several challenges must be addressed to realize the full potential of QC-HAP. Future work will focus on various directions. First, a critical challenge is developing feasible techniques to evaluate current quantum hardware capabilities, particularly coherence time and memory capacity, to bridge the gap between theoretical performance and practical implementation. These concerns are particularly significant given the early-stage development of quantum network hardware—a key enabler for scaling to multi-HAP quantum computing systems. Additionally, the unique characteristics of the stratospheric environment warrant careful consideration. For instance, the weather conditions might impact significantly the harvested solar power and hence affect the energy efficiency of the Quantum Computing-Enabled High Altitude Platform. Specifically, solar irradiance in the stratosphere is subject to seasonal variations. Therefore, it is essential to anticipate appropriate measures based on predicted weather conditions and to consider backup power sources, such as wind energy, which can be harvested through turbines installed on the surface of the HAP. Moreover, cosmic rays and stray background radiation are a main concern in quantum computing that threatens reliability to varying degrees [32]. This problem is accentuated in the stratosphere since the cosmic ray flux increases with altitude. However, the impact varies according to the qubit's type. For instance, ion trap qubits are less affected than superconducting qubits since the generated quasiparticles disrupt superconducting circuits directly. Therefore, the appropriate mitigation measures (e.g. hardware shielding or advanced error-correction) should be applied according to the considered quantum architecture to compensate for potential reliability degradation. Overall, future research should analyze how specific environmental factors affect quantum systems and develop robust designs for practical QC-HAP implementation and operation. Looking ahead, this aerial quantum solution will likely coexist with conventional data centers, operating cooperatively within a hybrid cloud computing framework enabled by 6G communications. This integration of quantum and classical technologies requires careful orchestration to deliver efficient and sustainable computing solutions that meet both application requirements and user expectations.

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