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Toward a Universal Quantum Computing Cloud: Characteristics and Requirements

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Abstract—Quantum computing is emerging as a powerful complement to classical computing, offering new computational paradigms across diverse quantum hardware architectures. As access to quantum resources expands, there is a need for a unified model to support interoperability, scalability, and ease of use. This paper introduces the concept of a *Universal Quantum Computing Cloud (UQCC)* and presents its essential characteristics at high levels—spanning service abstraction, virtualization, user experience, and system integration. By defining UQCC, we aim to support future development and adoption of cloud-based quantum platforms across research and industry.

Index Terms—cloud, cloud computing, quantum computing, quantum computing computing cloud, service oriented

I. INTRODUCTION

QUANTUM computing has emerged as a transformative paradigm that leverages fundamental quantum principles—such as superposition, entanglement, interference, parallelism—to tackle problems that are computationally infeasible for classical systems [1]. Over the past decade, rapid progress in quantum hardware, algorithms, and development environments has accelerated the transition of quantum computing from theoretical constructs to practical, cloud-delivered services [2]. Along the side of QC, cloud computing has evolved much more rapidly and reshaped how classical computational resources are consumed, enabling scalable, on-demand, pay-per-use access to infrastructure and platforms [3], [4]. The convergence of these domains—quantum computing and cloud computing—has led to the emergence of *quantum computing cloud*: a model where users remotely execute quantum algorithms on real quantum processors via cloud interfaces [5].

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Early demonstrations of this concept validated its feasibility. Devitt [6] showed that quantum computing experiments could be performed in the IBM Quantum cloud, paving the way for democratized access to quantum resources and broader participation from academia and industry. More recently, Grossi et al. [7] proposed a serverless architecture to further abstract quantum workloads from backend complexities, underscoring the importance of modularity, elasticity, and developer-friendly tooling in future quantum cloud ecosystems. A recent comprehensive survey by Nguyen et al. [18] highlights the evolution of quantum cloud platforms, taxonomies of service models, and critical challenges including hardware heterogeneity, limited standardization, and the absence of a unified abstraction framework. Their work emphasizes that future quantum cloud services must overcome these limitations by providing transparent, architecture-agnostic access across devices and programming paradigms.

To address this need, we introduce the concept of a *Universal Quantum Computing Cloud (UQCC)*—a next-generation framework designed to unify the access, control, and orchestration of diverse quantum computing systems under a single cloud-native infrastructure. In this paper, after discussing different types of quantum processing unit (QPU) in Section II, we formally define UQCC in Section III, describe levels of service abstraction in Section IV, outline its essential characteristics in Section V, and position it within the Gartner Hype Cycle in Section VI. This work aims to lay the foundation for future research, development, and deployment of interoperable quantum cloud ecosystems.

II. RELATED WORK

The fast advancement of quantum computing has prompted a parallel development of cloud-based quantum services. Early foundational efforts such as IBM Quantum Experience, now rebranded as IBM Quantum Platform, and Microsoft’s Azure Quantum Computing have demonstrated the viability of re-

TABLE I
COMPARISON OF QUANTUM QUBIT TECHNOLOGIES

Qubits Types	Where the Quantum Information is Stored	Example Companies	Status	Ref
Nuclear Magnetic Resonance (NMR)	Spins of atomic nuclei manipulated using radio-frequency pulses	EPFL	First demonstration of an actual quantum computer but it is not scalable beyond ~10 qubits	[8]
Superconducting qubits	Energy eigenstates of Josephson junction-based electronic resonant circuits	IBM, Google, IQM, Rigetti	Most mature, with 100+ qubit systems	[9]
Trapped-ion qubits	Ions trapped in electromagnetic fields; qubit is encoded in internal states of ions	IonQ, Quantinuum (Honeywell), Alpine Quantum	High fidelity gates; slower but very accurate	[10]
Photonics	Uses polarization, path, or time-bin encoding of photons	Xanadu, PsiQuantum, Quandel, Orca computing	Room temperature; good for networking, photon loss and scaling are issues	[11]
Quantum dot qubits	Electron spins confined in semiconductor nanostructures	Intel, TU Delft	Promising for integration with classical semiconductor tech	[12]
Topological qubits	Qubits encoded in Majorana fermions; immune to local noise	Microsoft	Experimental physics ongoing, high potential for fault-tolerant qubits	[13]
Neutral atom qubits	Qubits are encoded in the quantum states of individual neutral atoms (such as rubidium or cesium) that are trapped and controlled using arrays of optical tweezers or lattices.	Atom Computing, QuEra, Pasqal	It is feasible to trap and rearrange hundreds or thousands of atoms in scalable 2D arrays. and Rydberg interactions allow entanglement between non-neighboring qubits. It is suitable for both digital gate-based quantum computing and analog quantum simulation.	[14]
Diamond NV center qubits	Spin states of nitrogen-vacancy (NV) centers in diamond	Quantum Brilliance	Mostly for sensing; some use in computing	[15]
Donor atom qubits (e.g., Phosphorus in Silicon)	Spins of single atoms doped into silicon	Silicon Quantum Computing	Long coherence times; ultra-small footprint; hard to control and scale	[16]
Optomechanical qubits/Hybrid qubits	Combines mechanical vibrations with optical or microwave control for qubit encoding	Yale Quantum Institute	Research stage; potential use in memory and interfacing	[17]

motely accessible quantum resources. These platforms offer limited universality and interoperability but serve as precursors to the more comprehensive vision of UQCC.

Several papers have explored the architecture and performance of individual quantum cloud platforms [5], [6] and an up-to-date survey of all available quantum computing clouds is present in [18]. However, few works attempt a holistic definition or characterization of a truly universal quantum cloud system. Contrarily, since its commencement around 2017, classical cloud computing has been rapidly developed and it reached the level of productivity in only 8 years, as we will see in Sect. VI. Cloud computing introduced a transformative paradigm in which users access computing resources hosted on remote infrastructures, typically without needing to know the physical location of the hardware [3], [19].

To the best of our knowledge, this paper presents the first formal definition of a UQCC, synthesizing both the quantum computational requirements and cloud delivery models into a unified framework.

Quantum computing is fundamentally based on the concept of the *qubit*, the quantum analog of the classical bit. While classical bits take on definite values of either 0 or 1—typically

realized via transistor-based switching—qubits exploit the principles of quantum mechanics to exist in a superposition of states. Once excited, a qubit can assume a linear combination of both 0 and 1 until measurement causes it to collapse into one of the classical outcomes [20].

Four key properties differentiate qubits from classical bits: *superposition*, *entanglement*, *interference*, and *quantum parallelism*. Superposition allows a qubit to exist in multiple states simultaneously, enabling exponential scaling of quantum state space with the number of qubits. Interference is where the wave-like nature of particles/qubits causes their probability amplitudes to combine, either constructively or destructively, influencing the measurements. Entanglement is a uniquely quantum phenomenon in which the state of one qubit becomes intrinsically linked to the state of another—such that measuring one instantly affects the state of the other, regardless of the physical distance between them [21]. This interdependence is foundational to quantum algorithms and protocols. Quantum parallelism enables a quantum computer to process a superposition of inputs simultaneously, dramatically increasing computational efficiency for specific tasks.

To construct a functioning quantum computer, a QPU, must satisfy a set of criteria established by DiVincenzo [22]. These

criteria outline the minimal physical requirements necessary for scalable and practical quantum computation:

- A scalable physical system with well-characterized qubits,
- The ability to initialize qubits to a known fiducial state,
- Sufficiently long quantum coherence times,
- A universal set of quantum logic gates,
- Qubit-specific, high-fidelity measurement capability.

Various QPU technologies have been employed to build systems that satisfy these conditions, including superconducting circuits, trapped ions, photonic systems, and spin-based architectures. A comparison of existing qubits technologies and their associated QPU is provided in Table I [23], [24]. Although detailed discussion of QPU is beyond the scope of this paper, we notice that each QPU type has its own encoding scheme, execution model for quantum algorithms. As such, there is an increasing demand for a unified cloud-based platform that enables access to multiple types of quantum computing backends. This motivates the need for interoperability, service and architectural abstraction—core principles of the UQCC.

III. PROPOSED DEFINITION OF UQCC

In this section, we propose a formal definition of the UQCC for the first time in the literature. According to the Oxford Language Dictionary, the term *universal* refers to something “relating to or done by all people or things in the world or in a particular group; applicable to all cases.” Since its inception, cloud computing has become foundational to modern IT ecosystems—enabling what has been described as “everything that we currently do” in computing [3], [4]. In the context of quantum computing, the notion of universality is twofold. It encompasses both *computational universality*, referring to the ability to execute a full range of quantum algorithms, and *platform universality*, denoting the ability to access and operate across diverse quantum architectures via cloud-based services. Inspired by the desire of a easy to use quantum computing system on the cloud, we define the *Universal Quantum Computing Cloud* (UQCC) as:

A comprehensive pool of virtualized quantum resources accessible via the internet, which includes various heterogeneous quantum hardware systems. These resources can be dynamically reconfigured to accommodate variable workloads (scalability), allowing for optimal resource utilization. The infrastructure is typically accessed through a pay-per-use model, where guarantees are provided by the infrastructure provider via customized Service Level Agreements (SLAs), and usage is free from architectural constraints.

UQCC aspires to offer a unified, inclusive, and user-friendly suite of quantum computing services, thus contributing significantly to the democratization and practical deployment of quantum technologies.

IV. LEVELS OF SERVICE ABSTRACTIONS

This section categorizes the different levels of service abstraction relevant to UQCC. These abstractions define the interaction between users and quantum cloud resources, as well as the types of services that can be deployed and consumed [3]. Depending on the provided capabilities, UQCC can be described under five main service models as in Table II and in Figure 1. While quantum services inherently rely on classical counterparts for tasks like data preprocessing and quantum result post-processing, this paper focuses exclusively on the quantum aspects. For a detailed discussion of classical cloud abstraction layers, readers may refer to [3].

A. Application-as-a-Service (AaaS)

AaaS represents the highest level of abstraction in quantum cloud offerings and it is less popular in the classical computing paradigm, due to the complications of quantum data encoding, quantum algorithm for specific hardwares. At this level, users submit high-level queries or domain-specific problems to the service provider. The provider then selects and runs appropriate quantum and classical algorithms to deliver results. For example, an R&D department of an automotive company might request simulations for new painting materials with reduced CO₂ emissions and improved durability. The cloud provider would utilize quantum optimization and chemical modeling algorithms to return solutions, with minimal input from the end-user and reduce partly the latency.

B. Software-as-a-Service (SaaS)

SaaS provides end-users with access to cloud-hosted quantum software applications without requiring local installation or maintenance [25]. For instance, such as quantum machine learning or quantum chemistry simulation tools, available as browser-based services, exemplify SaaS in the quantum domain.

C. Platform-as-a-Service (PaaS)

PaaS abstracts underlying hardware and infrastructure while providing developers with a set of tools and APIs for building, testing, and deploying quantum applications. It acts as a bridge between low-level qubit operations and high-level application development. Amazon Braket is a good example which integrate a few types of QPU together.

D. Infrastructure-as-a-Service (IaaS)

IaaS involves the provisioning of raw PQUs to users, typically in the form of virtualized or time-sliced access to specific QPUs. Users can select particular QPUs (e.g., superconducting qubits or trapped ions) and execute custom circuits, with control over job submission, queue handling, and backend parameters.

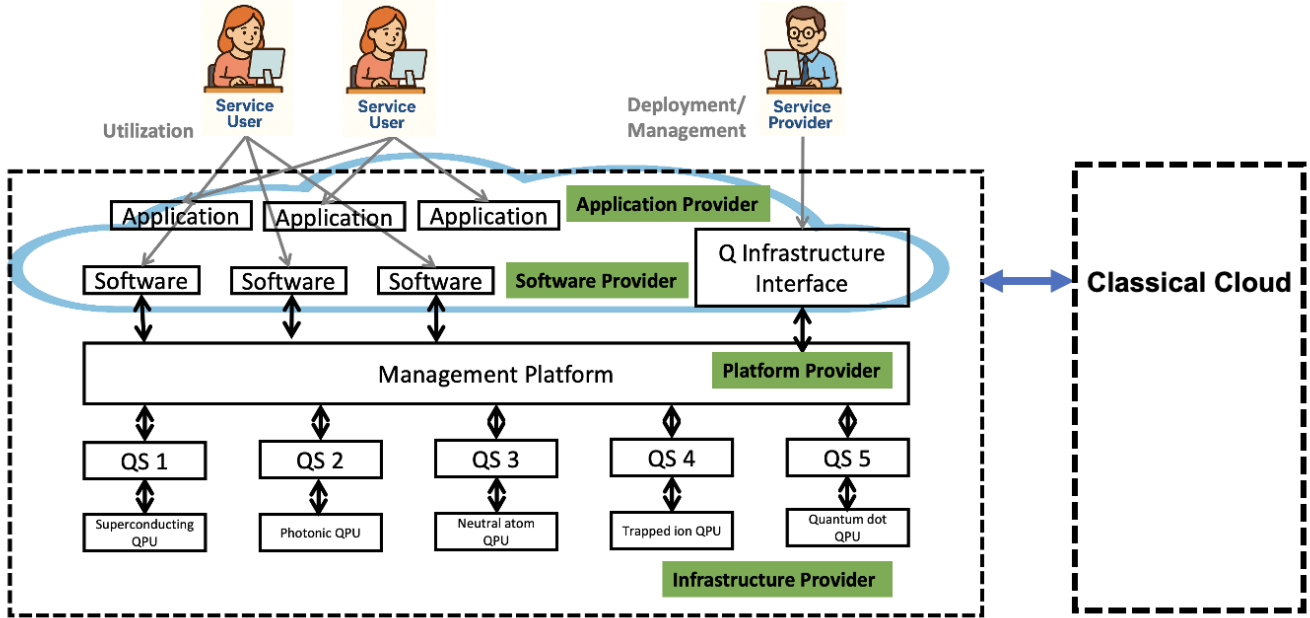


Fig. 1. UQCC abstraction layers ranging from the lowest level AaaS, SaaS, PaaS, to IaaS and uIaaS and the interaction with the Classical Cloud. See Discussion in Section IV.

TABLE II
COMPARISON OF QUANTUM CLOUD SERVICE ABSTRACTION LEVELS

Service Model	Abstraction Level	User Control
AaaS (Application-as-a-Service)	Highest	Minimal – user submits high-level goals
SaaS (Software-as-a-Service)	High	Low – predefined quantum apps via UI or API
PaaS (Platform-as-a-Service)	Medium	Medium – use SDKs/APIs for quantum programs
IaaS (Infrastructure-as-a-Service)	Low	High – job queues, backend configs
uIaaS (Universal-Infrastructure-as-a-Service)	Lowest (but most flexible)	High – unified access across hardware types

E. Universal-Infrastructure-as-a-Service (uIaaS)

uIaaS (or uHaaS—Universal Hardware-as-a-Service) extends the IaaS concept by offering unified access to a heterogeneous pool of QPUs. Rather than being confined to a single technology stack, users are able to run applications across various quantum devices via a common abstraction layer. This model is foundational to the concept of UQCC and enables scalable, architecture-agnostic quantum computation, where backend selection, resource allocation, and translation are handled transparently by the cloud provider.

V. ESSENTIAL CHARACTERISTICS OF UQCC

Because this is the first time UQCC is formally defined in the literature, we identify its core characteristics by synthesizing insights from both classical cloud computing and current quantum cloud service descriptions. To support this, we conducted a sentiment analysis of publicly available discussions and documentation related to quantum computing cloud. This analysis, in conjunction with established cloud computing principles [26], informs the key characteristics of UQCC as listed in Table III. These characteristics can be grouped into three thematic categories: service-oriented features, user-centric experience, and system-level capabilities.

A. Service-Oriented Characteristics

1) *Universality or Interoperability*: UQCC must support a wide range of quantum computing models (e.g., superconducting, neutral atom, trapped ion, photonic) as well as classical CPU and GPU in order to allow users to run diverse quantum-classical hybrid algorithms. The orchestration layer must provide semantic equivalence across devices: a circuit designed for a superconducting backend should produce functionally consistent results when deployed on trapped-ion or photonic hardware, despite differences in gate sets, connectivity, and error models. This includes hardware abstraction, QPU-agnostic programming interfaces, and compatibility with low level standard quantum instruction sets such as OpenQASM 3.0 [27], Quil [28] and Jaqal [29]. Recently, a mid-level compiler was designed to perform this integration MLIR [30].

2) *Service Abstraction and Modularity*: Similar as the service-oriented architecture (SOA) model for classical cloud [31], UQCC aims at offering multi-level services (AaaS, SaaS, PaaS, IaaS, uIaaS) (see Section IV.) The abstraction layer has to be modular, enabling seamless workload migration between levels. For instance, a workload developed at the PaaS level using Qiskit could be escalated to AaaS for domain-specific

TABLE III
ESSENTIAL CHARACTERISTICS OF UQCC GROUPED BY THEME

Characteristic	Definition / Features
Service-Oriented Characteristics	
Universality	Support for gate-based, annealing, topological, and hybrid QC models; QPU-agnostic interfaces
Service Abstraction	Multi-level services (AaaS, SaaS, PaaS, IaaS, uIaaS); user interaction flexibility
Pay-per-Use	Usage-based pricing like utilities; billing aligned with compute time or algorithm complexity
SLAs	Performance and reliability contracts between users and providers
User-Centric Characteristics	
Ease of Use	Intuitive interfaces; accessible via web portals or SDKs
User Experience Design	Emphasis on usability, accessibility, and responsiveness; UI follows web 2.0 practices
Access Anywhere	Remote access via internet regardless of geography; browser-based or API-driven tools
System-Level Characteristics	
Scalability	Ability to support many users, qubits, workloads, and distributed backends
Virtualization	Hardware abstraction for portability, fault tolerance, and load balancing
Interoperability	Cross-platform compatibility, circuit portability, support for hybrid workflows
Security	End-to-end encryption, isolation, access control, quantum-safe protocols

optimization or lowered to uIaaS for device-specific execution. This modularity requires middleware capable of dynamically translating circuits, handling classical–quantum orchestration, and optimizing placement of workloads across multiple QPUs.

3) *Pay-per-Use and SLAs*: UQCC services operate under dynamic, usage-based pricing models. UQCC must adopt dynamic usage-based pricing models, where billing reflects qubit time, gate depth, and error correction overheads. Unlike classical clouds, resource metering must also capture non-trivial factors such as shot counts, qubit connectivity, and compilation complexity. For example, AWS’s Braket has two pricing options: per-task price and per-shot price. Infrastructure and service-level agreements (SLAs) define performance guarantees, job turnaround times, and quality-of-service commitments [3], [19] through SLAs requirement such as availability, queue latency, job completion, execution fidelity, error rate bounds, throughput, interoperability, security, customer Support.

B. User-Centric Characteristics

1) *Ease of Use and Accessibility*: UQCC interfaces are designed for broad accessibility. Through web-based dashboards, SDKs, and APIs, users of varying expertise—from researchers to students—can access quantum resources remotely.

2) *User Experience Design*: Following best practices in web 2.0 and application usability, UQCC interfaces emphasize clarity, simplicity, and responsiveness. The design process includes user need analysis, function design, and implementation that minimizes the technical overhead for non-experts [32].

C. System-Level Characteristics

1) *Scalability*: UQCC is built to scale in multiple dimensions: number of users, concurrent job loads, and supported hardware architectures. This includes horizontal scaling across distributed quantum infrastructure providers, quantum platform management, shot and job queue management, and adaptive workload distribution.

2) *Virtualization and Resource Optimization*: Quantum calculation and classical post-processing resources are virtualized and pooled for efficient access and load balancing. These virtualized layers abstract hardware complexity, enable on-demand provisioning, and improve system utilization.

3) *Interoperability*: UQCC is inherently interoperable with various QPU types, classical systems, and hybrid workflows. It supports backend switching, unified APIs, and platform-independent circuit formats. Standardization efforts around intermediate formats (OpenQASM 3.0, QIR) and workflow orchestration APIs are critical for interoperability.

4) *Security*: Security in UQCC includes both classical and quantum-safe measures. End-to-end encryption, job isolation, secure identity management, and compliance with regulatory standards are essential. The system’s loose coupling, virtualization, and abstraction also minimize attack surfaces and protect user data [33] by unplugging parts of the systems when attacks happen.

VI. EMERGENCE OF UQCC

To contextualize the current state of Universal Quantum Computing Cloud (UQCC), we position this emerging technology on Gartner’s Hype Cycle [34]. This model is a widely accepted framework that illustrates the evolution of a technology’s maturity, adoption, and public perception through cycles of overenthusiasm, disillusionment, and eventual productivity [35]. As UQCC is introduced and defined for the first time in this paper, we argue that it currently resides at the earliest stage of the cycle—the *Technology Trigger* phase—characterized by the onset of technological breakthroughs and increasing interest from both academia and industry.

To provide a comparative perspective, we trace the trajectory of quantum computing itself across the Hype Cycle, as shown in Fig. 2. Beginning with the implementation of the first experimental quantum computer in 1998 [36], [37], the technology has taken approximately 24 years to transition from the *Technology Trigger* to the *Peak of Inflated Expectations*.

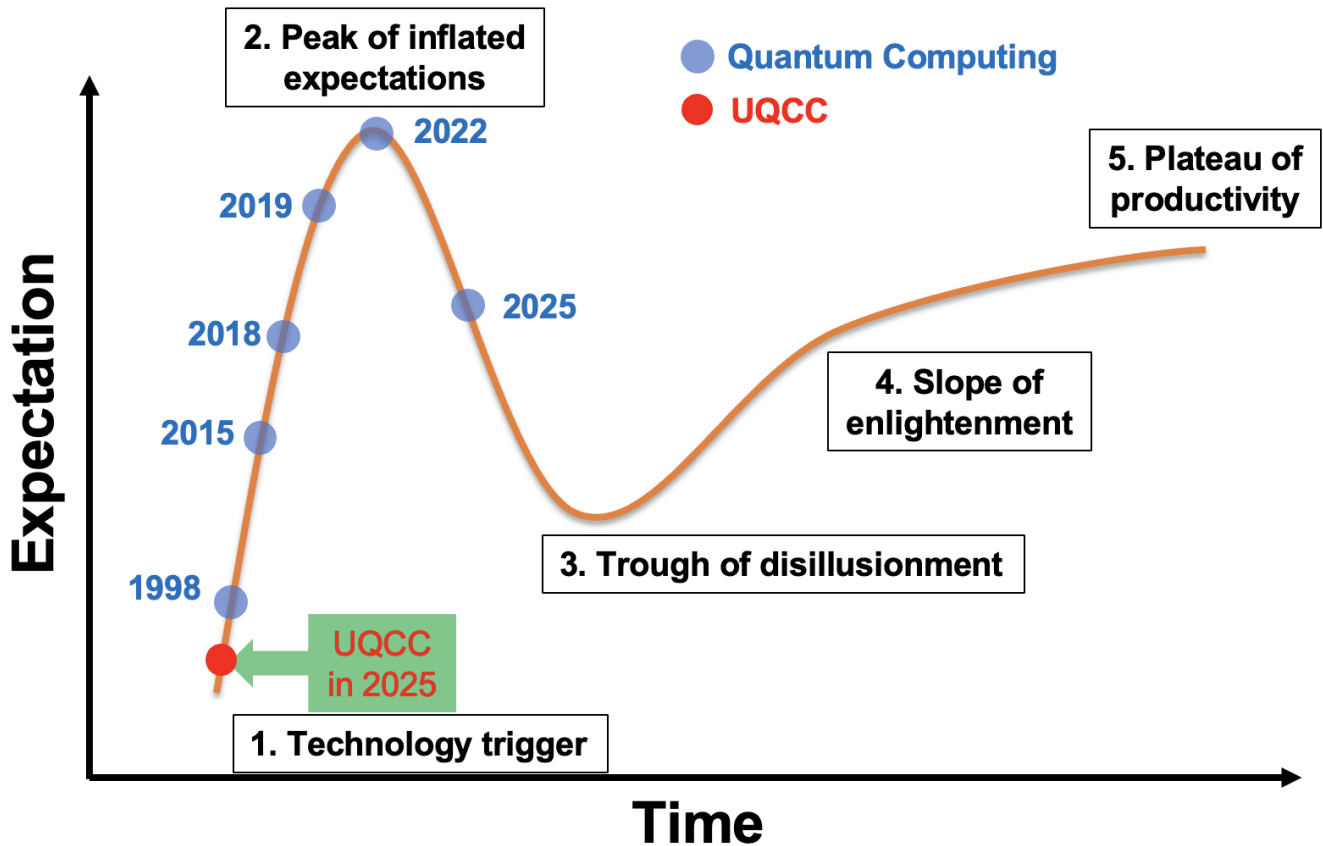


Fig. 2. Positioning of Quantum Computing and UQCC on the Gartner Hype Cycle. Blue circles represent the positions of quantum computing technology of different years while the Green box represents the position of UQCC.

This phase is marked by high visibility and overly optimistic projections regarding the technology’s transformative potential, often accompanied by a surge in research funding and media attention. From 2022 onward, expectations for quantum computing have shown signs of decline, signaling a movement toward the *Trough of Disillusionment*.

However, the duration a technology spends in each stage of the Hype Cycle varies considerably. For instance, cloud computing, which entered the cycle around 2007, required only eight years to reach the *Plateau of Productivity*. The pace of progression is influenced heavily by adjacent technological developments. In the case of quantum computing, persistent challenges such as qubit stability and the scalability of quantum processors have prolonged its path.

Given its foundational dependency on quantum hardware and scalable infrastructure, UQCC is still at the nascent stage of the *Technology Trigger*. Based on historical analogies and current trajectories, we project that UQCC may reach the *Peak of Inflated Expectations* by 2030, enter the *Trough of Disillusionment* by 2035, ascend the *Slope of Enlightenment* by 2040, and ultimately achieve the *Plateau of Productivity* by 2045.

VII. CONCLUSION AND FUTURE WORK

This paper introduced the concept of a UQCC, outlining its motivation, service abstraction layers, and essential characteristics. UQCC offers a unified, QPU-agnostic, scalable, and user-centric framework for quantum computing in the cloud.

Key contributions:

- Defined UQCC and its five characteristics.
- Compared classical cloud service models with quantum counterparts (AaaS, SaaS, PaaS, IaaS, uIaaS).
- Highlighted the evolution and technical diversity of QC and UQCC in the Gartner’s HYPE Cycle.

Limitations and Challenges

Despite the potential of UQCC, its essential characteristics involve inherent limitations and trade-offs that must be carefully considered:

- **Service-Oriented Constraints:** Universality across heterogeneous QPUs may obscure hardware-specific optimizations, leading to performance penalties. High-level abstractions (AaaS, SaaS) simplify adoption but restrict control, whereas low-level access (uIaaS) demands advanced expertise. Pricing models are further complicated by stochastic workloads, making cost prediction uncertain.

- User-Centric Challenges: Abstraction enhances accessibility but risks reducing transparency, hindering scientific reproducibility. Automated backend selection may favor latency over fidelity, producing biased outcomes or higher costs.
- System-Level Trade-offs: True virtualization of qubits is limited by physical constraints (e.g., no-cloning theorem), so “quantum hypervisors” can only approximate abstraction via emulation and transpilation. Multi-cloud scaling introduces heterogeneity in scheduling and calibration data, complicating orchestration. Interoperability requires intermediate representations but may discard unique hardware features.
- SLA-Specific Limitations: Quantum uptime is inherently volatile due to calibration cycles and hardware fragility. Latency guarantees are difficult under variable demand. Fidelity thresholds are statistical, subject to drift, and not absolute. Finally, pay-per-use models may lead to unpredictable costs, particularly for iterative algorithms such as VQE or QAOA.

Future directions:

- Consider a case study of a real deployment: simulating an application run across two QPU back-ends, to showing cost-and-latency breakdown
- Develop open standards for quantum-cloud APIs and SLAs.
- Create robust middleware for hardware abstraction and backend switching.
- Explore hybrid quantum-classical orchestration and deployment pipelines.
- Evaluate usability and performance metrics across quantum cloud platforms.

UQCC lays the groundwork for scalable and accessible quantum computing, accelerating its adoption in academia and industry.

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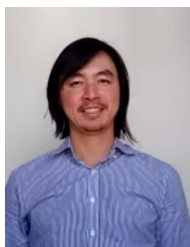
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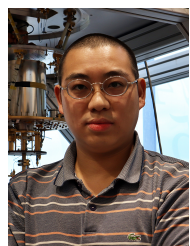
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