Quantum Ecosystem Development Using Advanced Cloud Services

Lalitha Nallamothula(✉)

Frisco, TX 75035, USA

Abstract. The four fundamental quantum phenomena of superposition, entanglement and tunneling are envisioned to give quantum computing the ability to solve complex problems in very low-resolution times as compared with classical computers. Quantum computing relies on various types of processors, frameworks, algorithms, and simulators which can be accessed using Cloud services. Quantum computers provide an incredible processing power to the users. Having these quantum capabilities as services over cloud to access through internet is called Cloud-based quantum computing. Many tech giants have connected their quantum computers to the cloud platform and provided access to internet users from various sectors to be able to build and run simple programs on them. Industry-leading companies have started capitalizing on the capabilities of quantum technologies. It is exciting to see potentially transformative applications in the quantum algorithm space. Quantum computing software projects have significantly increased in areas where complex problems could be solved in very low-resolution times. From computing to communications, signal processing, navigation systems, quantum solutions offer unprecedented level of performance, privacy, security, and speed. The existing single layer architecture of providing *Quantum as a service* is still very basic and makes it complicated for users to have a choice over the kind of applications they would like to implement. This is because the services are not distinct and relevant to the needs of the users. This paper attempts to study IBM's existing Quantum cloud platform and provides a multilayered enhanced approach with advanced quantum cloud services. This paper presents a new approach to develop a sophisticated quantum ecosystem to enhance the user base and quantum computing applications.

Keywords: Quantum computation · Quantum cloud services · Superposition · Entanglement · Quantum tunneling · Quantum annealing · Computational power

1 Introduction

Quantum computers get their phenomenal computing power by harnessing quantum properties namely, superposition, entanglement, tunneling, and annealing [1]. Quantum Cloud services are offered via the internet by many companies. Tech giants like Google, IBM, Microsoft, AWS began to offer cloud-based quantum computing services in hopes to herald the wave of this emerging technology [2]. Quantum Technologies are advancing way too fast and there is a clear need to revise the existing cloud computing models to suit

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quantum computing. The existing single layer architecture of providing *Quantum as a service* is still very basic and makes it complicated for users to have a choice over the kind of applications they would like to implement. This is because the services are not distinct and relevant to the needs of the users. This paper provides a multilayered enhanced approach with advanced quantum cloud services to develop a quantum ecosystem to enhance the user base and quantum computing applications.

In quantum computers, data is processed as qubits as opposed to regular bits in classical computing. Quantum computers need special types of processors and simulators that operate using quantum phenomena and are a lot different to classical computers [4–6]. There is also a huge learning curve in adapting to the new quantum specific software components, platforms, and interfaces to be able to program and run quantum circuits, algorithms, and web applications. In regular cloud computing, the layers of services are categorized as IaaS (Infrastructure as a service), PaaS (Platform as a service), FaaS (Functions as a service), and SaaS (Software as a service) [3]. This paper attempts to create a new quantum ready SOA (Service Oriented Architecture) model replacing the existing layers with quantum ready scalable services, while virtualizing software and hardware components of quantum computing. This approach makes quantum ecosystem development a lot easier by enabling the users to have choice over application specific needs and reduces the learning curve. This paper attempts to put this analysis in a perspective and creates a multilayered approach to IBM's quantum ecosystem development roadmap [2, 3, 6, 7].

The main functional benefits for this approach are in the areas of research, developing commercial applications and in educating and preparing the industry to be quantum ready. This multilayered architecture empowers the users with tools to use and knowledge to take advantage of quantum computing.

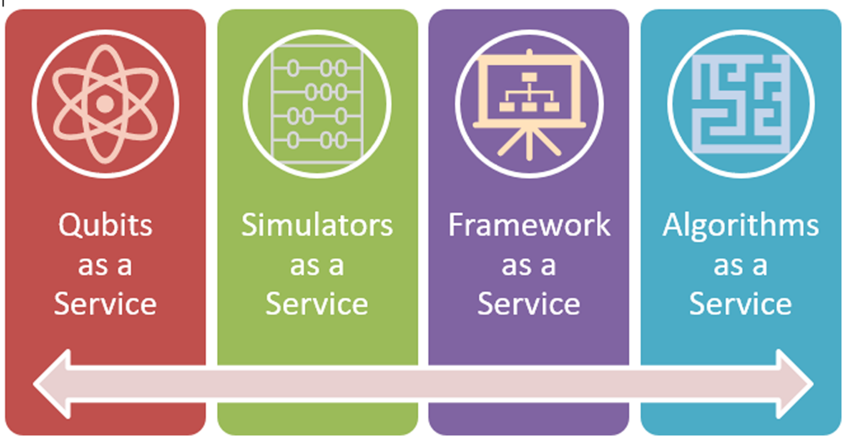

Fig. 1. Advanced quantum cloud services

Figure 1 shows the proposed multilayered architecture for advanced quantum cloud services.

The services include:

- *QuaaS – Qubits as a Service*
- *QsaaS – Quantum simulators as a Service*
- *QfaaS – Quantum framework as a Service*
- *QaaaS – Quantum algorithms as a Service*

2 Qubits as a Service

QuaaS – Qubits as a Service: A qubit is like a bit used in classical computing except that a qubit is a two-level quantum system with two possible quantum states. And these two basis qubit states are |0 > and |1 >. A qubit is essentially a carrier of quantum information. A variety of quantum processors have demonstrated the potential to control the quantum states using qubits. There are different types of qubits. The qubits that IBM uses are the superconducting transmon qubits made of superconducting materials. These qubits are fabricated by creating a difference in two isolated energy levels. Qubits developed in this manner are maintained at extremely low temperatures. The temperature is such that

$$k_B T \ll hf$$

where ***k***B is Boltzmann's constant, h is Planck's constant, f is frequency of the qubit and T is temperature. We need a quantum gate to control the qubit. Quantum gates are essential to describe the evolution of a quantum state. Some quantum gates are different to classical gates such as Hadamard gate H, phase shift gates. These quantum gates operate on quantum mechanical phenomenon such as superposition and entanglement.

A Bloch sphere representation of a qubit state is shown below. X, Y, Z are the cartesian coordinates of a Bloch sphere of unit length 1 [2, 3, 6, 7, 12] (Fig. 2).

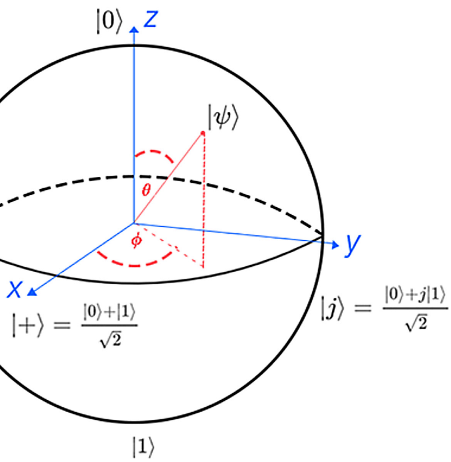

Fig. 2. Bloch sphere representation of a qubit

Quantum machines with qubits ranging from 5 to 5000 or more can be accessed by the users over the cloud. Whether the users are running IQP circuits (Quantum Polynomial Time) or QAOA circuits, (Quantum Approximate Optimization Algorithm), they would need a certain number of qubits. An array of different quantum computers with different qubit power can be networked over a quantum internet and can be accessed as cloud service. These quantum machines can either be a Q-network of photonic quantum computers, continuous variable quantum machines, annealer based machines or gate-based quantum machines [11, 12]. Having the potential to choose the number of qubits needed to run specific algorithms as a service would be an additional advantage to the users.

3 Simulators as a Service

QsaaS – Quantum simulators as a Service: Researchers and developers working on quantum algorithms and applications often need to simulate the operations of the quantum computation. A quantum simulator allows the users to simulate the behavior of quantum computer on a classical computer. The main drawback of a simulator is that it allows simulation for quantum computers with a smaller number of qubits. Since classical computers need complex numbers to store a computation based on n qubits. IBM currently has a variety of simulators for simulating quantum circuits and algorithms. There are different types of simulation strategies.

1. Schrodinger wavefunction based simulator
2. Clifford simulator
3. Extended Clifford simulator
4. Matrix product state simulator
5. General purpose simulator

These simulators use different simulation techniques such as simulating a quantum circuit using Schrodinger's wave function of the qubit's state vector as gates and applying instructions (Schrodinger wavefunction based simulator), or using a rank-based stabilizer decomposition technique to approximate the action of a quantum circuit, or a tensor network technique that uses MPS representation of a state, and so on.

Each of these simulators suit different needs of the users based on certain factors like number of qubits, noise modeling, number of shots per job, number of circuits to execute, input circuits and parameters. IBM currently supports a maximum of 300 circuits and 8192 shots per job. Clifford simulator supports a maximum of 5000 qubits. There is a current time limit of 10000 s job runtimes on simulators to avoid long running jobs [2, 3, 6, 7].

This service provides the users with the ability to run simulations on the encoding and decoding circuits in the process of quantum error correction. Physicists can make use of simulations to better formulate problems in physics beyond the Standard Model such that a way that they can be solved using quantum computing. If compared adiabatic quantum computing to gate-based quantum computing, it is equivalent in power to implement arbitrary unitary operations. The substantial difference between gate-based quantum computing and quantum annealers is that in gated based quantum computing, logical variables are mapped only to single qubits and not to chains (A. J. Abhari et al.) [16]. Quantum simulators provide a comprehensive and powerful service for these scenarios [18] (Fig. 3).

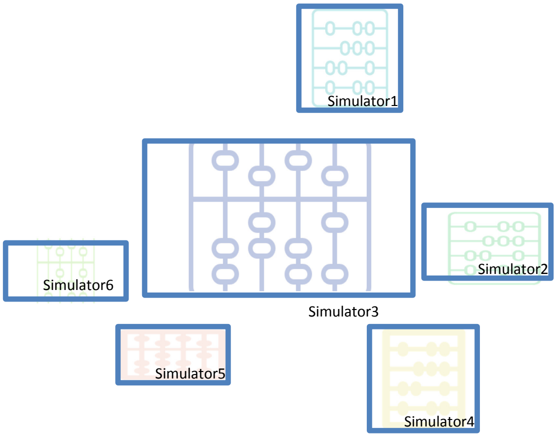

Fig. 3. Network of quantum simulators

4 Framework as a Service

QfaaS – Quantum framework as a Service: The design flow of a generic quantum architecture would consist of a technology independent optimizer followed by a technology dependent optimizer (QASM) and finally a quantum device/simulator (QPOL). The technology independent optimizer produces the QIR (quantum intermediate representation) and a technology dependent optimizer processes it into QASM (quantum assembly language). And finally, a quantum device/simulator processes it to a QPOL (quantum physical operations language) (Fig. 4).

QIR: quantum intermediate representation
QASM: quantum assembly language
QPOL: quantum physical operations language

IBM currently provides a secure environment to use cloud-based quantum services. It uses different programming tools, prebuilt application models and simulators accessible via the IBM cloud. IBM's Quantum system services are built upon cryogenic electronics and are all based on superconducting qubit technology. Providers are used to control the services. A provider is essentially a container unit of sublevels called hubs, groups, and projects. Hubs contain groups, and groups contain projects [2, 3, 6–8] (Fig. 5).

A job instance is created for every task that we attempt to run using a quantum service. These jobs can be used to track the tasks and to retrieve the results. Providers are categorized as private or open based on the user account.

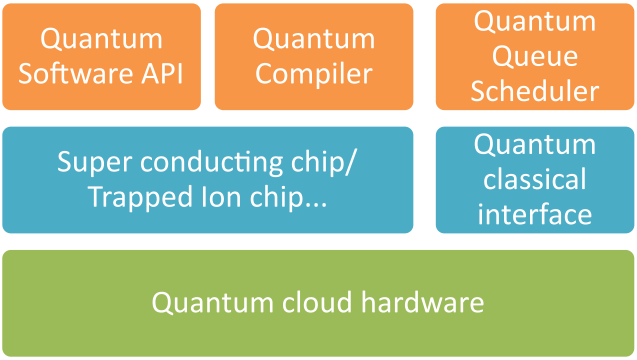

Fig. 4. Quantum architecture framework

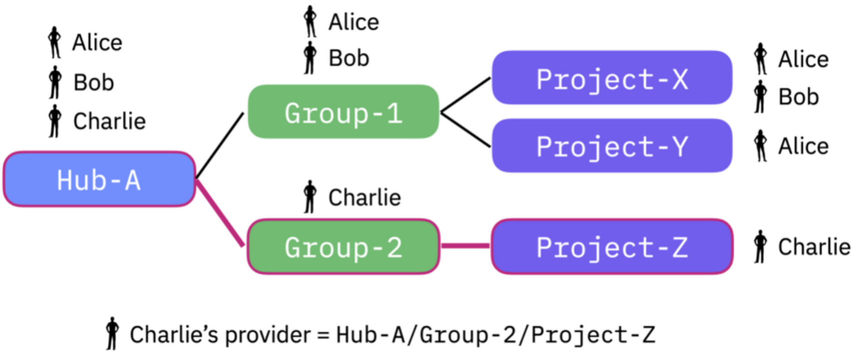

Fig. 5. Hubs, Groups and Projects [30]

IBM has created a transparent roadmap to enhance the current capabilities in quantum computing. Through an open-source collaborative vision, IBM is working on developing an advanced quantum computing stack with a robust cloud-based API. In the next two to five years, IBM's focus is on three areas with respect to quantum computing: Kernels, Algorithms and Models. Quantum Kernel developers focus more of hardware and developing circuit APIs that enhance features like faster runtimes, being able to store programs, and running more circuits in less time. Quantum Algorithm developers explore new applications of quantum circuits. Model developers essentially think in terms of creating families of prebuilt frameworks by combining the foundations provided by kernel and algorithm developers.

Quantum framework as a service provides a unified environment and programming choice of available frameworks for the users to perform classic-quantum hybrid programming. It provides quantum classical interfaces, underlying hardware options and software programming selection array to compiler options to find the suitable architecture framework for the users [12–17, 21–29].

5 Algorithms as a Service

QaaaS – Quantum algorithms as a Service: The application areas of quantum computing breakthrough spread across multiple industries such as Finance, quantum chemistry and many others. Having a set of prebuilt tools accelerates the development of quantum application. A variety of quantum software projects, quantum web applications, quantum games are deployed on a quantum cloud network. Gate-based projects and annealing based projects are being developed using different quantum devices, algorithms, frameworks, and quantum programming languages. It is not always easy to decide the right architecture for your project.

Firstly, there are three different types of quantum computing models.

a) Quantum annealing
b) Quantum simulations
c) Universal quantum computing

IBM uses its very own Qiskit, an open-source SDK needed to interact with Quantum systems and simulators. It has a library of quantum algorithms specific to the applications. Be it machine learning, which consists of algorithms like QSVM, VQC (Variational Quantum Classifier), or Nature in general which consists of quantum biology, quantum chemistry and physics related algorithms, or finance algorithms such as optimization algorithms, Qiskit together with Python are considered evolving ecosystems.

This *QaaaS – Quantum algorithms as a Service* provides a library of some important and basic algorithms such as quantum optimization algorithms, quantum gaming algorithms, and so on. There are many available quantum simulators grouped by programming language. Some examples are: OpenQASM, Q#, QML, QuTiP etc. Having access to such a library as a service gives the ability to accelerate the learning and development processes for the users [9, 10, 20, 29]. This service should provide the ability to access a set of well-defined circuits or building blocks of a more complicated model to explore quantum computational advantage (Fig. 6).

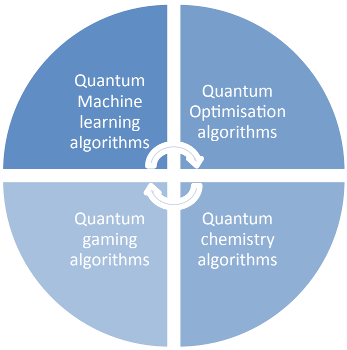

Fig. 6. Quantum algorithm library

6 Conclusion

In summary, with the rise of quantum computers, we need a network of Quantum computing software tools and cloud services to carry out extensive research and to provide effective solutions. From computing to communications, signal processing, navigation systems, quantum solutions offer unprecedented level of performance, privacy, security, and speed. The number of qubits quantum computers can support are increasing tremendously and so are the noise mitigation and correction strategies making quantum computing a rising field. The existing single layer architecture of providing Quantum as a service is still very basic and makes it complicated for users to have a choice over the kind of applications they would like to implement. This is because the services are not distinct and relevant to the needs of the users. This paper attempts to study IBM's existing Quantum cloud platform and provides a multilayered enhanced approach with advanced quantum cloud services. This paper presents a new approach to develop a sophisticated quantum eco-system to enhance the user base and quantum computing applications. As described in sections I to V, this approach to create a new quantum ready SOA (Service Oriented Architecture) model replacing the existing single layer of Quantum as a service with a multi layered quantum ready scalable services makes quantum ecosystem development a lot easier and incredibly faster. Section I provides an introduction about the current problem and the idea behind this model. Section II covers the first service *QuaaS – Qubits as a Service.* Section III covers the second service *QsaaS – Quantum simulators as a Service.* Section IV covers the third service *QfaaS – Quantum framework as a Service* Section V covers the fourth service *QaaaS – Quantum algorithms as a Service.* This model also increases the quantum user base from various industries, researchers, and academia considering its effective and plug and play services over the cloud. This model gives users a tremendous leap over existing cloud computing capabilities and thus helps increase usability.

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