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Benchmarking Quantum Algorithms on Xanadu, IBM, and Google Quantum Computers

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***Abstract*—NISQ-era Quantum computers are slowly getting deployed to real-world use cases. Quantum Computation facilitates speedy solutions to a wide range of complex problems. To monitor progress towards more advanced devices, we can characterize their dynamics and analyze their performance using certain benchmarks for determining their computational capabilities. In our research, we simulated and analyzed Bose Hubbard Hamiltonian in Google, IBM, and Xanadu Quantum Computers and calculated the accuracy and speed. Then we solved one of the NP-hard problems called the Maximum clique and computed its execution speed.**

Keywords : IBM, Google, Xanadu, Quantum Computers, Speed, Accuracy, Benchmarking

I. Introduction

Quantum computing harnesses collective properties of quantum states, like superposition, interference, and entanglement, to perform calculations. Quantum computing not only helps to handle larger data sets but also solves complex problems faster. There are 2 types of benchmarking: systems and applications. System benchmarks help us analyze fundamental characteristics of quantum computers like circuit depth, gate density, and width. Application benchmark evaluates performance at specific tasks. In this study, common benchmarks have been used for three different Quantum Service Providers to keep consistency in benchmarking algorithms. The task was to simulate Bose Hubbard Hamiltonian in Xanadu Borealis, Strawberry Fields, IBM Belem Quantum Computer, IBM QASM Simulator, Google qsim simulator, and Quantum Virtual Machine. Results were analyzed thus aiming to benchmark the accuracy and speed of all Quantum Service Providers. A similar methodology is used for solving the Maximum Clique Problem[23].

II. Quantum Computers and Virtual Machines

A. IBM

International Business Machines is one of the top leading companies providing cutting-edge quantum computing facilities to people around the globe. IBM Eagle manufactured in 2021, has the highest number of qubits as developed by the company. Its architecture has 127 superconducting qubits. The superconducting architecture uses electric current flowing through superconducting materials to store and process information. IBM provides access to quantum simulators running on the user's device and cloud and also quantum computers. The quantum systems that were used in this research from IBM:

IBM QASM - It is a simulator that simulates quantum circuits in ideal cases and also with noise modeling. Automated selection of simulation method is done based on the input circuits and parameters.

IBM Belem -A quantum processor with superconducting architecture and 5 qubits. The version we used was 1.0.49

B. Xanadu

Xanadu Quantum Technologies develops Photonic computers. Recently developed photonic Quantum Computer Borealis has 216 squeezed-state qubits. It is devised to offer full programmability, high-speed processing, and capable of quantum computational advantage. Xanadu's architecture is modular and capable of scaling up to one million qubits. This quantum tech company is developing fault-tolerant modules that work together to generate, entangle, and process thousands of qubits. They use linear optical quantum computing[25]. The quantum systems that were used in this research from Xanadu:

Strawberry Fields - A python-based library that helps to design, simulate and use photonic quantum computers.

Xanadu Borealis - The new photonic quantum computer Borealis launched recently this year has 216 squeezed-state qubits and is predicted to exhibit quantum advantage[16].

C. Google

Google provides remote access to quantum processors and simulators. Algorithms were simulated in the Google qsim simulator and Quantum Virtual Machine (QVM). In QVM the rainbow processor was used for simulating both the algorithms. The QVM machine imitates the quantum computer with noise added in the process. qsim lets us program 40-qubits circuits on a 90-core Intel Xeon workstation and it is incorporated in Cirq. We used the Cirq python library as used to simulate the model in the qsim simulator. The quantum systems:

GOOGLE qsim Simulator - qsim simulator has been written in C++. It utilizes AVX/FMA instructions and gate fusion with the help of OpenMP to attain advanced quantum circuit simulations.

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GOOGLE Quantum Virtual Machine - The quantum virtual machine is a virtual Google quantum processor that can run circuits by using the virtual engine interface. Behind this interface, it uses simulation with noise data to mimic Google quantum hardware processors with high accuracy. In internal tests, the virtual and actual hardware is within experimental error of each other. Additionally, it supports the internal use of the high-performance qsim simulator, for fast execution of larger circuits[15].

The details of the Quantum Computers/Simulators that were worked on are shown in the table below[20].

Sr. No	Name	Processor /Simulator	Number of Qubits
1	Xanadu Borealis (photonics)	Borealis Processor	216 squeezed qubits
2	Strawberry Fields	-	-
3	GOOGLE Quantum Virtual Machine	Rainbow	-
4	GOOGLE qsim Simulator	Full wave function simulator	-
5	IBM QASM Simulator	General, context-aware	32
6	Ibmq_Belem (superconducting)	Falcon r4t	5

Fig. 1. Quantum Computers/Simulators

III. METRICS

Applications benchmarking is done to compare the performance of the simulators and quantum computers.

The 2 key system metrics used for comparing are:-

1) Speed

The amount of time taken by the quantum computer or simulator to run a particular program helps us understand which system is the fastest and most reliable for speedy solutions. Wall time is been considered because it includes waiting time for the resources. It's the difference between the start and end times of the program[2].

2) Accuracy

The accuracy of the process is measured using the metric state fidelity. This is a measure of distance between density operators. It is defined as

$$F(\rho,\sigma) = (\operatorname{tr}\sqrt{\sqrt{\rho}\sigma\sqrt{\rho}})^2 \tag{1}$$

where ρ and σ are the desired quantum state and resultant quantum state after computing in a quantum simulator or computer[25].

As the current quantum computers have different modalities and different special use cases, we selected a task from quantum simulation and optimization. Thus we choose algorithms that have already specified workflows in all the quantum simulators and computers of interest. We Identified bose hubbard hamiltonian simulation for quantum simulation and Maximum Clique Problem for optimization.

IV. BOSE HUBBARD HAMILTONIAN SIMULATION

Bose Hubbard Model can describe spinless Bosonic atoms in optical lattice experiencing repulsive or attractive interactions. It can be generalized and extended to Bose-Fermi mixtures which are referred to as Bose-Fermi Hubbard Hamiltonian.

The many-body hamiltonian describing dynamics of systems of particles with pairwise interaction in second quantized notation is written as

$$\hat{H} = \sum_{\sigma}\int d\mathbf{r}\psi_a^{\dagger}(\mathbf{r})\hat{H}_{sp}\hat{\psi}_{\sigma}(\mathbf{r}) + \frac{g}{2}\sum_{\sigma\sigma'}\int d\mathbf{r}\int d\mathbf{r}'\hat{\psi}_{\sigma}^{\dagger}(\mathbf{r})\hat{\psi}_{\sigma'}\left(\mathbf{r}'\right)\hat{\psi}_{\sigma'}(\boldsymbol{r})\hat{\psi}_{\sigma}\left(\mathbf{r}'\right) \tag{2}$$

σ represents internal degrees of freedom of atoms
g is coupling strength
$\hat{H}_{sp}$ is a single particle hamiltonian of one particle and $\hat{\psi}_{\sigma(r)}$and $\hat{\psi}_{\sigma}^{\dagger}(r)$ are the annihilation and creation operators having spin σ at the lattice location r. With tight-binding approximation, expansion of operators is carried out in the Wannier basis set. It's assumed that the particles are tightly bound to the lattice sites in such a way that they occupy only the lowest energy band.

$$\begin{aligned}\hat{\psi}_{\sigma}^{\dagger}(\mathbf{r}) &= \textstyle\sum_{i=1}^{N} w^{*}\left(\mathbf{r}-\mathbf{r}_i\right)\hat{b}_{i\sigma}^{\dagger} \\ \hat{\psi}_{\sigma}(\mathbf{r}) &= \textstyle\sum_{i=1}^{N} w\left(\mathbf{r}-\mathbf{r}_i\right)\hat{b}_{i\sigma}\end{aligned} \tag{3}$$

here $\hat{b}_{i\sigma}^{\dagger}$ and $\hat{b}_{i\sigma}$ describe particle creation and annihilation given by the wavefunction $w\left(\mathbf{r}-\mathbf{r}_i\right)$ at the lattice location i. Therefore, the old Hamiltonian under new approximation using new operators gives the general hubbard hamiltonian.

$$\begin{aligned}&\hat{H}_{\mathrm{H}} = -\textstyle\sum_{\sigma}\sum_{(i,j)}\left[g_{ij}b_{i\sigma}^{+}\hat{b}_{y\sigma} + h.c.\right] + \sum_{\sigma\sigma'}\sum_i \frac{U}{2}\hat{b}_{i\sigma}^{+}\hat{b}_{i\sigma'}^{\dagger}\hat{b}_{i\sigma'}\hat{b}_{i\sigma} \\ &J_{ij} \equiv \textstyle\int d^3rw^{*}\left(r-r_i\right)\hat{H}_{sp}w\left(r-r_j\right) \\ &U \equiv g\textstyle\int d^3\mathbf{r} \mid w\left(r-r_i\right) \mid^4\end{aligned} \tag{4}$$

In case of one component bosonic species trapped in a periodic lattice, the Hamiltonian reduces to standard Bose-Hubbard Hamiltonian.

$$\hat{H}_{BH} = -J\sum_{<i,j>}(\hat{b_i^{\dagger}}\hat{b_j} + \hat{b_j}\hat{b_i^{\dagger}}) + \frac{U}{2}\sum_i \hat{n_i}(\hat{n_i}-1) - \mu\sum_i \hat{n_i} \tag{5}$$

$< i, j >$ represents summation on all neighboring lattice sites i, j. Chemical potential μ sets the number of particles and J describes the boson mobility in lattice called the hopping amplitude. The first term in the equation describes tunneling between lattice sites whereas the second term represents on-site interaction. For attractive interactions, we have $U < 0$ and for repulsive $U > 0$. Unless specified the interaction term is considered to be repulsive in the model. This model is used to study the entanglement of ultra-cold atoms as well[1][9]. This model is simulated in various available quantum computers/simulators. Aim was to simulate and find the average execution time and average state fidelity which account for speed and accuracy respectively. Hubbard hamiltonian was defined and the parameters were set as hopping transition J = 4, on-site interaction U = 4.4, and timestep t = 1.084. Further we moved on simulating the time evolution and dynamics of Bose Hubbard hamiltonian. Conversion of this hamiltonian to quantum circuits was done on various platforms for studying this.[19]

V. MAXIMUM CLIQUE PROBLEM

It is a non-deterministic algorithm and belongs to the set of NP-hard problems. A clique of a graph is a sub-graph of a graph in such a way that all points of the sub-graph

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are interconnected. In this problem, the goal was to find one maximum clique of an arbitrary undirected graph. To generate random graphs we utilize the Erdos–Rényi (ER) model. The model is represented as G=(p,q), where p is the set of vertices/nodes and q can be thought of as a weighting function for our undirected graph. When q increases from 0 to 1, the model is likely to use additional number of edges in the graph than before[11]. In our Renyi graph, we considered p=10 and q=0.5 to generate random undirected graphs. The idea used for solving the problem is recursion. More edges were added to the initial list of edges to check if it still forms a clique or not. Vertices are added until a point comes where we don't find any cliques. Here the process stops and is back-traced to find the maximum clique. Figure 1 shows the graph that was generated using ER model and figure 2 gives a simplified version of all vertices and edges highlighting the maximum clique[13][3][4].

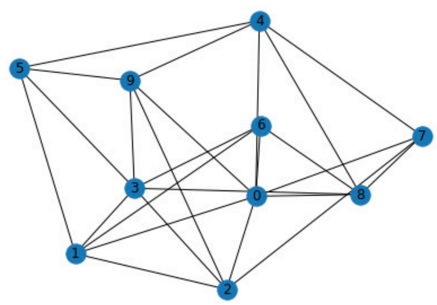

Fig. 2. ER graph with 10 nodes

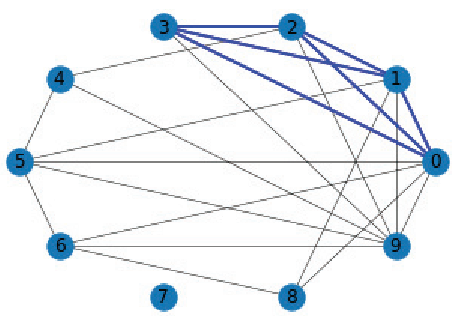

Fig. 3. Maximum Clique in ER graph

There are several applications for solving this problem like patterns in telecommunication traffic, computer vision, pattern recognition, design of error correcting codes, etc.

VI. Results

A. Bose Hubbard Hamiltonian

1) Speed

From Fig 4. it is clear that **IBM Belem executed the Hubbard simulation in the least time whereas Borealis took the longest time**. Interestingly IBM QASM Simulator and GOOGLE qsim Simulator speeds have been found to have comparably close execution speed.

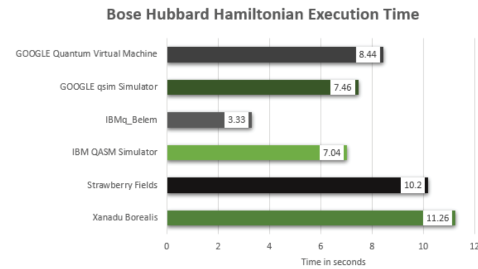

Fig. 4. Bose Hubbard Execution Time

2) State Fidelity

For the bose Hubbard hamiltonian final and initial states are specified for the equation. This helped determine the state fidelity which signifies the accuracy of solving the quantum algorithm. From Fig.5 it can be seen that Google Quantum Virtual Machine and IBM Belem have similar state fidelities. Similarly, strawberry fields and Xanadu Borealis have very close values for state fidelity. **The lowest fidelity is for Borealis whereas the highest is for IBM Belem and GOOGLE Quantum Virtual Machine**.

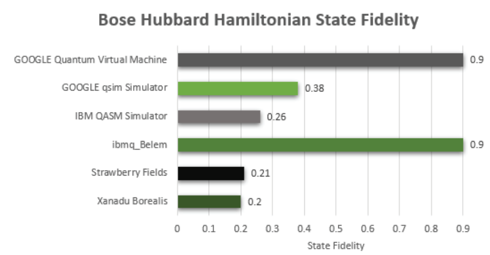

Fig. 5. State Fidelity

B. Maximum Clique Problem

1) Speed

Again, IBM Belem executed the maximum clique problem the fastest whereas Xanadu's strawberry fields took the longest time for execution. Borealis, GOOGLE Quantum Virtual Machine and GOOGLE qsim simulator have comparably close speeds for solving this problem. See Fig.6

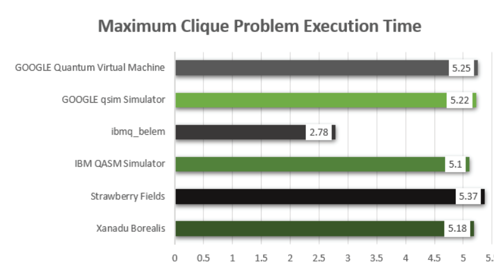

Fig. 6. Maximum Clique Execution Time

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VII. Discussion

IBM is at the frontier of quantum technology development. It has been developing new systems to date with increased number of qubits. The accuracy and speed of the systems developed by IBM are at the forefront as it is one of the oldest quantum tech firms working on superconducting qubits. Xanadu is a relatively new quantum system provider working on photonic quantum computers which is still undergoing a lot of research. Within a small time scale, photonic quantum computers have proved quantum computational advantage over few other systems and seeing the level of progress it's making they are of great potential use in the future. Here, the comparison was not amongst the qubit systems but rather quantum computers to execute two different problems. Amongst all the simulators that were benchmarked, **the speed and accuracy of IBM QASM was found to be exhibiting eminent results. Similarly, amongst all quantum computers, IBM Belem was found to be at the foremost**. Surprisingly IBM Belem had higher fidelity than the simulator. More experiments should be done to examine this result. Comparing systems with superconducting and photonic architecture is not completely possible. What was studied, was how photonics is emerging in comparison to superconducting systems and its computational accuracy for two different algorithms.

VIII. Future Prospects

Two benchmarks were devised for solving two peculiar problems in 6 different quantum systems and simulators. The research can be extended by devising other benchmarks and trying to find solutions to various new problems to analyze the computational capabilities across newer systems and simulators. There are various other quantum computers and simulators apart from the ones that were worked on in this study, all of them are possible candidates for research and each one has its own unique computational capacity. Companies like IQM, D waves, and Strangeworks also have a great future prospectus and it would be of great interest to analyze which system architecture photonic or superconducting is doing faster and for what type of problem.

IX. Conclusion

Assessment of potential capabilities of different quantum computers and simulators which are essential in understanding newer technologies and increasing the spectrum of further research is significant although challenging. Performance benchmarking accelerates the progress in quantum computing. Benchmarking is also a measure of analyzing a company's performance of products, services, and operations, against other companies. The key is to design benchmarks that are useful, scalable comprehensive for different systems. Benchmarking in quantum computing is more complicated because of the availability of a variety of quantum computing systems. Our aim is to achieve complete effectiveness as newer systems are coming into the picture and advancing at different rates. Benchmarks would enable us to compare the potentials of all available quantum computers and our rapidly growing computational capabilities.

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