Investigation on Quantum Computers

Zaher Mohammed Faruk

**FINAL YEAR BSC PROJECT REPORT 2023/2024**

This report is presented in partial fulfilment of the requirements for the award of the degree of B.Sc. with Honours in Physics

1. Abstract

This project presents an evaluation of two leading quantum computing platforms: IBM Quantum (which utilises superconducting qubits) and Xanadu’s photonic quantum systems (both accessible via the PennyLane Python library) [1]. Their performance in solving quadratic unconstrained binary optimisation (QUBO) problems, benchmarking metrics such as computational efficiency (execution time, resource usage), solution accuracy (approximation ratio), and error resilience (gate errors for IBM, photon loss for Xanadu) were tested [2].

The study highlights the fundamental differences between the two architectures. For instance, Xanadu’s photonic systems demonstrate advantages in parallel processing for specific QUBO instances, while IBM’s superconducting qubits excel in iterative gate-based optimisation routines. Scalability challenges, hardware-specific error mitigation strategies (e.g., dynamical decoupling for IBM, photon loss correction for Xanadu), and the role of software frameworks like PennyLane in enabling hybrid quantum-classical workflows were analysed in depth.

By testing these platforms with QUBO combinatorial optimisation problems, this work clarifies what is their practical utility and limitations. The results, supported by reproducible code (see Appendix), offer insights for researchers and developers in selecting quantum technologies tailored to combinatorial optimisation tasks. This analysis shows the importance of platform-specific algorithm design and the need for advancements in error correction to bridge the gap between theoretical potential and real-world applicability [3].

1. Acknowledgements

We sincerely thank the following people and organisations for their invaluable support, which were instrumental in making this scientific report possible:

- Dr Mark Hughes: His endless support and in-depth knowledge on Quantum Computing assisted me heavily.

- IBM: We are deeply thankful to IBM Quantum for providing access to their state-of-the-art quantum computing platform. Their advanced superconducting qubit technology enabled us to execute and benchmark quantum algorithms effectively. Additionally, we appreciate the extensive documentation and support available through the IBM Quantum platform, which significantly enhanced our understanding and implementation of quantum circuits.

- Xanadu Quantum Technologies: We express our gratitude to Xanadu Quantum Technologies for granting access to their photonic quantum computing platform and for providing the powerful PennyLane framework. The flexibility and user-friendliness of PennyLane allowed us to efficiently program and simulate quantum systems, while its compatibility with various quantum backends proved invaluable in conducting comparative studies.

1. Introduction

Quantum computing has emerged as a transformative computational approach over the past decade, leveraging principles of quantum mechanics to address problems that are difficult for classical systems. Among the diverse hardware architectures under development, superconducting qubit-based systems (exemplified by IBM Quantum) and photonic quantum computing platforms (pioneered by Xanadu Quantum Technologies) represent two leading approaches. This study provides a systematic comparison of these architectures, evaluating their performance in solving quadratic unconstrained binary optimisation (QUBO) problems - a class of combinatorial optimisation challenges with applications in logistics, finance, and materials science [4].

Technological Foundations

IBM Quantum uses superconducting transmon qubits, built using Josephson junctions. They are operated at cryogenic temperatures (≤ 15mK) to maintain quantum coherence. These systems execute gate-based quantum circuits, relying on high-fidelity single - and two-qubit operations (e.g., √𝑋, CNOT) optimised via the Qiskit framework. The architecture’s strong point is in its compatibility with iterative hybrid algorithms such as the Quantum Approximate Optimisation Algorithm (QAOA), which iteratively refines solutions through classical feedback loops [5, 6].

Xanadu’s photonic platform utilises squeezed light states in continuous-variable (CV) quantum computing. Photonic qubits (encoded in photon number or quadrature states) propagate through programmable interferometers, enabling Gaussian Boson Sampling (GBS) and CV variational algorithms. This architecture operates at room temperature and uses inherent parallelism in photonic networks, making it suited for tasks that require high-dimensional state manipulation [7, 8].

Architectural Divergences

1. Qubit Realisation:

IBM Quantum:

Superconduing transmon qubits depend on cryogenic infrastructure, operating at temperatures below 15mK, to reduce themal noise- achieved using dilution refrigerators [6]. These systems perform well in single-qubit gate operations, reaching high-fidelity levels above 99.9%, but encounter challenges in two-qubit gate fidelity, which typically sits around 99.5% [6].

In terms of coherence, 𝑇1 (energy relaxation time) ranges from 100 to 150 microseconds, while 𝑇₂ (dephasing time) falls between 50 and 100 microseconds [6]. While cryogenic cooling allows for precise microwave control, it also has scalability limitations, due to the complexity of wiring and constraints on qubit density as systems grow.

A Visual Comparison of IBM Quantum and Xanadu Quantum Technologies

|  |  |  |
| --- | --- | --- |
| Feature | IBM Quantum | Xanadu Quantum Technologies |
| Qubit Type | Superconducting transmon qubits | Photonic (squeezed light states) |
| Operating Temperature | Cryogenic (≤ 15mK) | Room temperature |
| Key Algorithm | QAOA (gate-based) | Gaussian Boson Sampling |
| Error Profile | Gate errors, decoherance | Photon loss, decector inefficiency |
| Strengths | Iterative hybrid optimisation | Parallel photonic processing |

Research Objectives

This work benchmarks both platforms through the lens of QUBO problem-solving—a task demanding both combinatorial search efficiency and resilience to noise. Using Qiskit (IBM) and PennyLane (Xanadu), we implement and optimise quantum algorithms under realistic noise models, quantifying performance via:

* **Computational efficiency**: Circuit depth, runtime, and resource utilisation.
* **Solution quality**: Approximation ratio and Hellinger fidelity against ideal simulations.
* **Error resilience**: Mitigation strategies (e.g., dynamical decoupling for IBM, post-selection for Xanadu).

Additionally, we evaluate the role of software frameworks in bridging theoretical models and physical hardware. PennyLane’s cross-platform compatibility enables direct comparison of photonic and superconducting workflows, while Qiskit’s pulse-level control permits fine-grained characterisation of gate errors [9, 10].

By elucidating the trade-offs between these architectures, this study aims to inform the selection of quantum technologies for industry-relevant optimisation tasks. Furthermore, it identifies critical challenges - such as photon loss mitigation and qubit connectivity - that must be addressed to achieve quantum advantage in practical settings.

1. Theory and Computational Approach

**Solving the QUBO Problem with Quantum Computing**

The Quadratic Unconstrained Binary Optimi**s**ation (QUBO) problem is a type of optimi**s**ation problem**.** It involves finding the optimal solution to a quadratic function where the variables are binary, meaning they can only take the values 0 or 1. The goal is to minimise (or maximise) this function without any additional constraints on the variables. QUBO problems are particularly notable because they can represent a wide variety of combinatorial optimisation issues, making them highly versatile and applicable to numerous real-world scenarios. Their importance has surged with the advent of quantum computing, which promises more efficient solutions to these complex problems [11] .

Mathematical Formulation of QUBO

Mathematically, the QUBO problem is expressed as follows:

Minimize f(x) = ∑i ai xi + ∑i < j bij xi xj

Where:

* xi are the binary variables, i,e., xi ∈ {0,1}
* ai are the coefficients for the linear terms
* bij are the coefficients for the quadratic terms

Matrix Representation

The QUBO problem can also be formulated in matrix notation. Let Q be a symmetric matrix where Qii = ai and Qij = bij for i ≠ j. The function then becomes:

f(x) = xTQx

Where:

* x is a vector of binary variables
* Q is a symmetric matrix containing the coefficients [12]

Example of QUBO function:

Consider a simple QUBO problem with three binary variables x1, x2, and x3:

f(x1, x2, x3) = - x1 – x2 – x3 + 2x1x2 + 2x1x3 + 2x2x3

This can be represented in the Matrix form as:

The objective function is:

f(x) = (x1 x2 x3)

**Solving the QUBO Problem with Quantum Computing**

**Xanadu Quantum Technologies**

**Solving the QUBO Problem with a simulation of a Quantum Computer via PennyLane:**

The QUBO Problem was solved using, the “default.qubit” device on PennyLane which is simulator for testing and development purposes. It doesn't directly connect to any specific Xanadu quantum hardware. For actual Xanadu hardware to be used, specifying a device such as "X8" or "Borealis”. These devices are part of Xanadu's photonic quantum computing systems. The QUBO problem was solved via this method, and the code was broken down into various sections each representing a different part of the QUBO function.

The code broken down into it’s various steps:

1) The Hamiltonian

H = 0.5 \* qml.Identity(1) + \

0.5 \* qml.PauliZ(1) @ qml.PauliZ(4) + \

0.5 \* qml.PauliZ(2) @ qml.PauliZ(3) + \

0.5 \* qml.PauliZ(3) @ qml.PauliZ(5) + \

0.5 \* qml.PauliZ(4) @ qml.PauliZ(4)

print(H)

The Hamiltonian (H), is defined as a combination of the tensor products of the Pauli – Z operators and the identity operator:

Here:

* I is the identity operator
* Zi represents the Pauli – Z operator acting on the qubit i
* ZiZj represnts a coupling term between the qubits i and j

This Hamiltonian encodes the QUBO problem. The coefficients of ZiZj represent the interaction weights, and the terms correspond to local biases. These interactions determine the energy landscape of the system, with the goal being to find the configuration of qubits that minimises H, which corresponds to solving the QUBO problem. The eigenvalues of H represent possible energies of the system, and the ground state (lowest energy eigenvalue) corresponds to the optimal solution of the QUBO problem [13].

2) Device Setup

dev = qml.device("default.qubit", wires=H.wires)

The device default.qubit simulates a quantum computer using qubits. The number of qubits is determined by the number of wires in the Hamiltonian H.

3) Defining the Circuit

@qml.qnode(dev)

def circuit(params):

for param, wire in zip(params, H.wires):

qml.RY(param, wires=wire)

return qml.expval(H)

Mathematical Intepretation:

The quantum circuit applies a series of parameterised rotations on each qubit:

Where the following equation is the rotation operator around the Y axis of the Bloch sphere:

After the applying the rotations, the expectation value of H is measured:

The rotations prepare a quantum state that depends on the parameters θ. The expectation value corresponds to the energy of the system for the given parameters. The goal is to minimise by optimising the parameters [14].

For the first equation, ∣ψ⟩ is the quantum state after the circuit has applied transformations, ⨂i is the tensor product applied across all qubits and it signifies that is applied independently to each qubit, is the rotation operator for the i-th qubit which performs a rotation by the angle θi around the Y – axis of the Bloch sphere, ∣0⟩ is the initial state of the qubit, which is the "ground state" in quantum computing. For the second equation RY (θ) is the rotation operator that rotates a qubit by angle θ around the Y – axis [15].

4) Optimisation Loop

params = np.random.rand(len(H.wires))

opt = qml.AdamOptimizer(stepsize=0.5)

epochs = 200

for epoch in range(epochs):

params = opt.step(circuit, params)

The optimisation process adjusts the parameters {} to minimise the expectation value of H:

The Adam oprimiser updates the prameters using gradient based optimisation:

=

Where η is the learning rate (stepsize) [16].

5) Sampling from an Optimised Circuit

dev = qml.device("default.qubit", wires=H.wires, shots=1)

@qml.qnode(dev)

def circuit(params):

for param, wire in zip(params, H.wires):

qml.RY(param, wires=wire)

return qml.sample()

Here, the circuit is modified to sample from the quantum state prepared by the optimised parameters {}. Each sample corresponds to a bitstring that represents a potential solution to the QUBO problem. The sampling process corresponds to a measurement in the computational basis. The probabilities of obtaining each bitstring are determined by the squared amplitudes of the quantum state:

In the context of quantum mechanics, this represents a projective measurement. The sampled bitstring with the lowest energy (as evaluated by H) corresponds to the optimal or near-optimal solution to the QUBO problem.

**Solving the QUBO Problem Using Real Quantum Hardware via PennyLane**

The QUBO problem was solved using the X8 device on PennyLane, which is part of Xanadu's photonic quantum computing systems. Unlike the default.qubit device, which is a simulator for testing and development purposes, the X8 device utilises real quantum hardware. This device leverages photonic qubits to perform quantum computations. The QUBO problem was addressed via this method, and the code was broken down into various sections, each representing a different part of the QUBO function. By utilising the X8 hardware, we achieve quantum computational benefits that are not possible with classical computers, demonstrating the potential of photonic quantum computing in solving complex optimisation problems [17].

**A comprehensive analysis of the mathematical framework underlying the X8 CPU architecture:**

The X8 architecture leverages advanced photonic integrated circuits (PICs) to manipulate and control light at the quantum level. These PICs are fabricated using silicon nitride (Si3N4) waveguides, which offer low propagation loss and high nonlinearities, essential for efficient quantum operations. The device integrates multiple components such as beam splitters, phase shifters, and squeezing operations to perform complex quantum computations.

At the core of the X8 system is the use of squeezed states of light, represented mathematically as:

Where S(r) is the squeezing operator defined by:

Here, r is the squeezing parameter, a is the annihilation operator, is the creation operator. These squeezed states have reduced noise in one quadrature, and increased noise in the conjugate quadrature, which enhances the sensitivity of quantum measurements. The architecture employs temporal division multiplexing (TDM) to increase the number of modes, represented as n, and enhance the computational power without increasing the physical footprint of the device. The quantum state evolution is described by the unitary operator U:

Where are the phase parameters, and are the Hamiltonians of individual components such as beam splitters and phase shifters. The X8 device operates at cryogenic temperatures (approximately 0.1 K) to minimise thermal noise and maximise coherence times. Superconducting nanowire single-photon detectors (SNSPDs) are used to detect single photons with high efficiency and low dark counts, ensuring accurate readout of quantum states.

The X8 architecture by leveraging these advanced technologies and mathematical principles, achieves quantum computational benefits that are not possible with classical computers, demonstrating the potential of photonic quantum computing in solving complex optimisation problems [18].

**An indepth look into the hardware behind the X8 CPU:**

A diagram of a programmable transformation

AI-generated content may be incorrect.

Figure 1: Quantum Circuit showcasing Xanadu's X8 Chip

This features eight quantum modes, numbered 0 to 7, which are organised into four pairs: (0,4), (1,5), (2,6), and (3,7). Each pair undergoes a process known as two-mode squeezing, facilitated by an S2 gate, which generates entangled photon pairs. Initially, the quantum modes—comprising signal photons (with a wavelength of 1549.3 nm) and idler photons (1536.6 nm)—begin in a vacuum state. The S2 gate then manipulates these states into a two-mode squeezed vacuum (TMSV) state, with the squeezing parameter r determining the outcome. If 𝑟 is 0, the state remains a vacuum; if 𝑟 is 1, a TMSV state is formed. To maintain phase coherence, the phase parameter 𝜙 is set to 0.

Following this, a 4×4 unitary transformation is carried out using an interferometer built from Mach-Zehnder (MZ) interferometers and rotation gates, which operate on both signal and idler modes. Lastly, photon-number resolving detectors measure the number of photons present in each quantum mode.

The eight modes intialised in the vaccum state, undergo squeezing with parameters r. These modes are then entangled using a fixed two-mode U(2) transformation, which acts like a 50/50 beam splitter with a set input phase, resulting in two-mode squeezing at the output. Next, programmable four-mode rotation gates (SU(4) transformation) are applied to each four-mode subspace, represented by the U4 boxes in the diagram. Finally, each of the eight modes is measured individually in the Fock basis [19].

**Strawberry Fields and PennyLane**

PennyLane is a software library for quantum computing, quantum machine learning, and quantum chemistry. It provides an interface to a range of quantum hardware and simulators, making it easier to implement variational quantum algorithms by combining quantum circuits with classical machine learning techniques. A key feature of PennyLane is its use of quantum gradients, allowing users to optimise quantum circuits with classical gradient-based methods. The library supports multiple quantum backends, including IBM Q, Rigetti Forest, and Xanadu’s Strawberry Fields, enabling seamless integration with different quantum platforms. Built on Python, PennyLane is easy to use and works well with other scientific computing and machine learning libraries [9].

Strawberry Fields, developed by Xanadu, is a specialised software platform for continuous-variable quantum computing using photonic systems. It provides tools for simulating and executing quantum circuits that involve Gaussian and non-Gaussian states and operations. Rooted in quantum optics, it leverages photonic qubits, where information is encoded in the quantum states of light, such as squeezed and coherent states. Strawberry Fields allows users to design, optimise, and run quantum circuits on both simulated and real photonic quantum hardware. With a Python library and built-in support for PennyLane, it facilitates the development of hybrid quantum-classical algorithms, making it a valuable tool for research in quantum machine learning and quantum chemistry [20].

References

[1] IBM Quantum. 2024. IBM Quantum. <https://quantum.ibm.com/functions>. [accessed 2024 Nov 27].

[2] Xanadu | Research. (2024). Xanadu.ai. <https://www.xanadu.ai/research>. [accessed 2024 Nov 27].

[3] Quantum circuits. (2024). Pennylane.ai. <https://docs.pennylane.ai/en/stable/introduction/circuits.html>. [accessed 2024 Nov 27].

[4] IBM Quantum Experience - Dashboard. (n.d.). IBM Quantum Experience. <https://quantum-computing.ibm.com/>.

[5] Welcome to Qiskit’s documentation! — Qiskit 0.7 documentation. 2019. Qiskitorg. <https://qiskit.org/documentation/>.

[6] Quantum Computing. 2021 Feb 9. IBM Research. [accessed 2024 Nov 27]. <https://research.ibm.com/quantum>.

[7] Aqeeb I, Arka, Kumar B, Kim R, Kim H, Rao Doppa J, Pande P. 2020. HeM3D: Heterogeneous Manycore Architecture Based on Monolithic 3D Vertical Integration. ACM Transactions on Design Automation of Electronic Systems. doi:https://doi.org/10.1145/3424239. [accessed 2023 Dec 6]. <https://arxiv.org/ftp/arxiv/papers/2012/2012.00102.pdf>.

[8] dougfinke. Quantum Computing Report - Market Analysis, News & Resources. Quantum Computing Report. <https://quantumcomputingreport.com/>.

[9] PennyLane. pennylaneai. <https://pennylane.ai/>.

[10] Quantum. Quantum. <https://quantum-journal.org/>.

[11] Mathworks, “Mel Frequency Cepstral Coefficients,” Mathworks.com, 2020, doi: <https://doi.org/1061245463.woff2>.

[12] F. Glover, G. Kochenberger, and Y. Du, “Quantum Bridge Analytics I: a tutorial on formulating and using QUBO models,” 4OR, vol. 17, no. 4, pp. 335–371, Nov. 2019, doi: <https://doi.org/10.1007/s10288-019-00424-y>.

[13]“Introduction to Quantum Computing | PennyLane Codebook,” Pennylane.ai, 2025. <https://pennylane.ai/codebook/introduction-to-quantum-computing?form=MG0AV3> (accessed Jan. 16, 2025).

[14] “qml.Rot,” Pennylane.ai, 2025. <https://docs.pennylane.ai/en/stable/code/api/pennylane.Rot.html> (accessed Jan. 20, 2025).

[15]“RYGate | IBM Quantum Documentation,” IBM Quantum Documentation, 2024. <https://docs.quantum.ibm.com/api/qiskit/qiskit.circuit.library.RYGate>.

[16] J. S. John, “AdamD: Improved bias-correction in Adam,” arXiv.org, 2021. <https://arxiv.org/abs/2110.10828> (accessed Jan. 20, 2025).

[17] “Xanadu | X-Series,” Xanadu.ai, 2025. <https://xanadu.ai/products/x-series/?form=MG0AV3> (accessed Feb. 06, 2025).

[18] A. Ranjan, T. Patel, H. Gandhi, D. Silver, W. Cutler, and D. Tiwari, “Experimental Evaluation of Xanadu X8 Photonic Quantum Computer: Error Measurement, Characterization and Implications,” Zenodo (CERN European Organization for Nuclear Research), pp. 1–13, Nov. 2023, doi: <https://doi.org/10.1145/3581784.3607058>.

‌[19] J. M. Arrazola et al., “Quantum circuits with many photons on a programmable nanophotonic chip,” Nature, vol. 591, no. 7848, pp. 54–60, Mar. 2021, doi: <https://doi.org/10.1038/s41586-021-03202-1>.

[20] “Strawberry Fields,” Strawberryfields.ai, 2023. <https://strawberryfields.ai/> (accessed Feb. 14, 2025).

‌

‌

**Appendix**

**QUBO Problem solved with various devices**

Simulation of a Quantum Computer (device: default.qubit):

**A screenshot of a computer

AI-generated content may be incorrect.**A screenshot of a computer program

AI-generated content may be incorrect.

A white rectangular object with black text

AI-generated content may be incorrect.

Executing Quantum Algorithms on Xanadu's X8 Hardware (device: strawberryfields.X8):

A screenshot of a computer program

AI-generated content may be incorrect.

Executing Quantum Algorithms on Xanadu's Borealis Hardware (device: borealis):

A screenshot of a computer program

AI-generated content may be incorrect.

Executing Quantum Algorithms on Xanadu's Aurora Hardware (device: Aurora):

A screenshot of a computer program

AI-generated content may be incorrect.