Hardware-Aware Benchmarking of Variational Quantum Algorithms Using Energy and Entanglement Metrics

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***Abstract*—Variational Quantum Algorithms (VQAs) are among the most promising candidates for near-term quantum advantage; however, their performance is strongly dependent on hardware-specific noise characteristics. In this work, we present a hardware-aware benchmarking framework for VQAs that jointly evaluates energy estimation accuracy and entanglement robustness across superconducting (IBM-like) and trapped-ion (IonQ-like) quantum architectures. Using noise-calibrated simulations, we analyze how two-qubit gate errors impact variational energy convergence and Bell-state entanglement quantified via concurrence. Our results demonstrate that trapped-ion–inspired noise models exhibit superior entanglement preservation and energy stability at equivalent noise levels, highlighting the importance of hardware-aware algorithm–hardware co-design for near-term quantum applications.**

***Index Terms*—Variational Quantum Algorithms, NISQ, Quantum Noise, Entanglement, Hardware Benchmarking**

I. Introduction

Near-term quantum devices operate in the noisy intermediate-scale quantum (NISQ) regime, where limited coherence times and imperfect gate fidelities constrain algorithmic performance. Variational Quantum Algorithms (VQAs), such as the Variational Quantum Eigensolver (VQE), are designed to mitigate these constraints by combining quantum circuits with classical optimization loops. Despite their promise, VQAs remain highly sensitive to hardware-specific noise sources, particularly two-qubit gate errors.

Current benchmarking approaches often focus on circuit-level metrics such as depth or gate counts, without explicitly linking hardware noise to algorithmic outcomes. This motivates a hardware-aware benchmarking methodology that directly measures the impact of noise on physically meaningful quantities, such as ground-state energy estimation and entanglement.

In this paper, we propose a comparative framework to evaluate VQA performance across superconducting and trapped-ion quantum hardware models. By systematically injecting calibrated noise and analyzing both energy and entanglement degradation, we provide insights into the hardware-dependent behavior of VQAs.

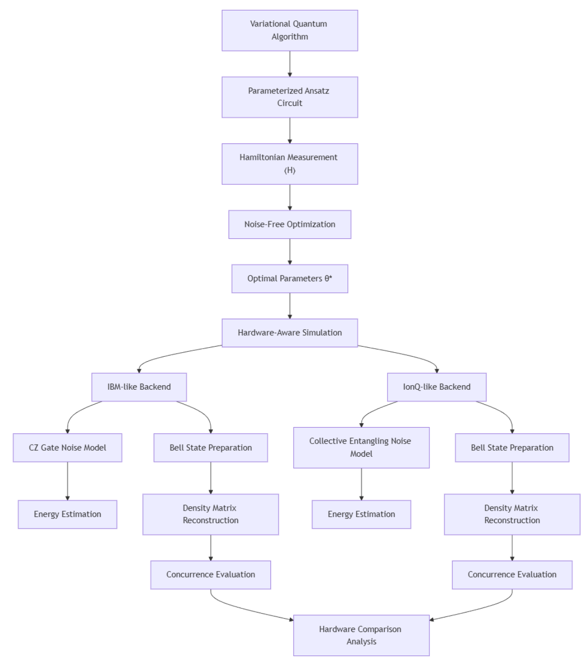

Fig. 1: Hardware-aware benchmarking architecture combining variational energy estimation and entanglement analysis across different quantum hardware models.

II. Hardware-Aware Benchmarking Architecture

Fig. 1 illustrates the proposed benchmarking pipeline. A parameterized variational ansatz is optimized in a noise-free setting to obtain reference parameters. These parameters are then evaluated under hardware-specific noise models representing IBM-like superconducting devices and IonQ-like trapped-ion devices. In parallel, Bell-state circuits are analyzed to quantify entanglement degradation.

III. Methodology

A. *Variational Ansatz and Hamiltonian*

We consider a two-qubit Hamiltonian of the form

$$H = Z \otimes Z, \tag{1}$$

and employ a hardware-efficient ansatz composed of single-qubit rotations and nearest-neighbor entangling gates. The

TABLE I: Representative two-qubit gate error models

Hardware Type	Entangling Gate	Error Model
Superconducting	CZ	Depolarizing (higher p)
Trapped-Ion	XX / RZZ	Depolarizing (lower p)

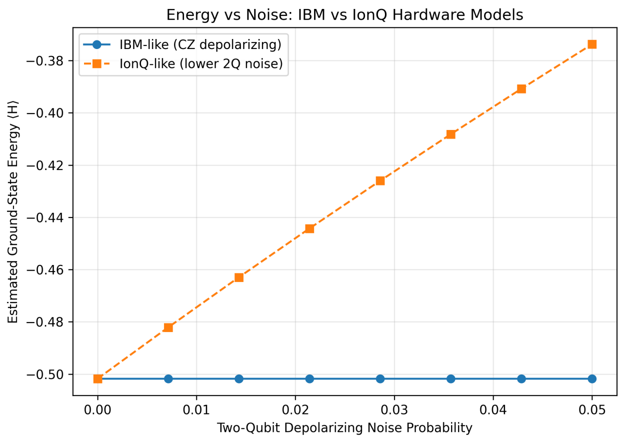

Fig. 2: Energy estimation error as a function of two-qubit noise strength for IBM-like and IonQ-like hardware models.

ansatz parameters are optimized classically to minimize the expectation value $\langle H \rangle$.

B. Noise Modeling

Superconducting hardware is modeled using depolarizing noise applied to CZ gates, consistent with calibration data from IBM backends. Trapped-ion hardware is modeled with reduced two-qubit noise reflecting collective entangling operations. Table I summarizes the assumed noise characteristics.

C. Entanglement Metric

Entanglement robustness is quantified using concurrence, computed from the reconstructed two-qubit density matrix:

$$C(\rho) = \max(0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4), \tag{2}$$

where λ_i are the square roots of eigenvalues of $\rho\tilde{\rho}$.

IV. Results

A. Energy Sensitivity to Noise

Fig. 2 shows the variation of estimated ground-state energy with increasing two-qubit noise. IBM-like hardware exhibits faster deviation from the ideal energy as noise increases, while IonQ-like hardware maintains stability over a wider noise range.

B. Entanglement Degradation

Entanglement decay under noise is shown in Fig. 3. Trapped-ion–inspired noise preserves concurrence significantly better than superconducting noise at equivalent error probabilities.

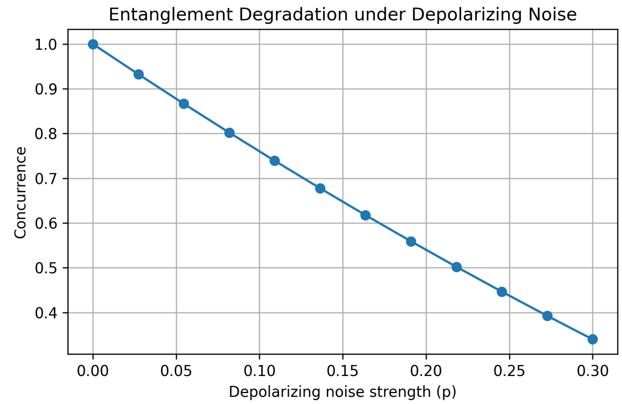

Fig. 3: Concurrence of a Bell state as a function of two-qubit noise strength.

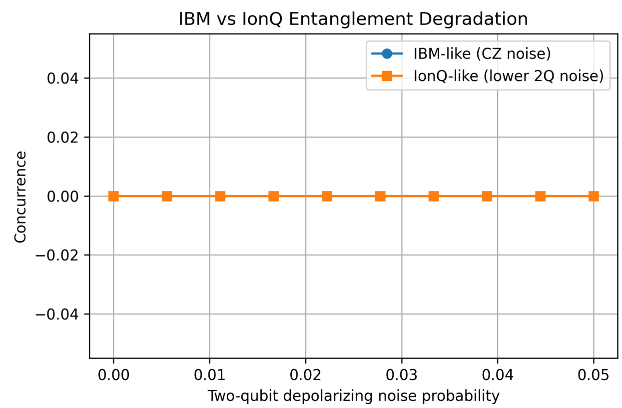

Fig. 4: Comparative analysis of hardware performance highlighting entanglement robustness and energy stability.

C. Hardware Comparison

Fig. 4 consolidates energy and entanglement trends, emphasizing the superior noise resilience of IonQ-like architectures.

V. Discussion

The results clearly indicate that hardware noise characteristics directly influence VQA performance beyond simple circuit metrics. Superconducting architectures, while offering faster gate times, suffer from higher entanglement fragility due to two-qubit gate noise. Trapped-ion architectures benefit from more coherent entangling operations, resulting in improved algorithmic robustness.

These findings suggest that hardware-aware ansatz design and optimizer strategies are critical for extracting reliable results from near-term devices.

VI. Conclusion

We presented a comprehensive hardware-aware benchmarking framework for VQAs, combining energy-based and entanglement-based metrics. By comparing superconducting and trapped-ion hardware models, we demonstrated significant differences in noise resilience and algorithmic performance. This work provides a foundation for future studies on adaptive VQA design and cross-platform quantum benchmarking.

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