2023 양자정보경진대회 지정문제

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Classification

Quantum Information Fundamentals: Greenberger-Horne-Zeilinger (GHZ) state

Background

A Greenberger-Horne-Zeilinger (GHZ) state is a type of multipartite entangled quantum state. An n-dimensional GHZ state is represented as follows:

$$|GHZ\rangle = \frac{|0\rangle^{\otimes n} + |1\rangle^{\otimes n}}{\sqrt{2}}$$

The most recent Nobel prize in Physics was shared by Anton Zeilinger for his experimental demonstration of Bell's inequality using the GHZ state [1]. The GHZ state is intriguing due to its numerous applications, such as quantum communication. However, to make these applications practical, error mitigation is crucial.

Note: You don't need to solve every problem! Feel free to tackle the ones that best suits your interests and background knowledge.

Problem

The goal of this challenge is to explore methods for constructing GHZ states with minimal errors. The first method is readout error mitigation, and the second method is zero-noise extrapolation which involves a pulse-level adjustment to your circuit. Lastly, we will investigate how to mitigate the noise in transmon qubits.

1. Building a GHZ state, running it on a real quantum hardware, applying readout error correction, and implementing quantum communication using GHZ states

   - Build a quantum circuit to create a 4-qubit GHZ state.
   (*Optional: Build a quantum circuit to create a 4-qubit W state)

   - Execute the circuit on a real quantum device and plot the histogram. Does it look like the intended state?

   - Among the various errors that may have affected your results, let's address readout errors. You have two options: you can either implement your own error mitigation scheme or utilize an existing Sampler API from Qiskit Runtime. To implement on your own, refer to references [2][3] to learn about readout error mitigation and proceed with its implementation. If you prefer to use the existing API, refer to [4] and set the resilience level to 1.

- Now, let's implement quantum communication using your circuit. Implement the scheme in "Part 2. One-Hop Bidirectional Quantum Communication" in reference [5]. Compare the results obtained from a simulator and a real quantum hardware.

2. Improving your GHZ circuit with pulse-level calibration (for a simplified two-level Hamiltonian). In the case of superconducting quantum computers, quantum gates are implemented through microwave pulses. You can optimize the pulses to minimize gate errors. One standard technique for canceling diabatic errors through pulse shaping is called DRAG [6]. An overview of other classes of quantum optimal controls such as GRAPE and CRAB is here [7]. Consider a two-level Hamiltonian for this problem. We will disclose specific parameters of the Hamiltonian during the event.

- Generate a pulse schedule for the circuit from problem 1-1.

- For this sub-problem, we will give you pulse parameters that are off tune for the problem Hamiltonian. Your task is to reconstruct your GHZ circuit using the given pulse gates. Then, run that pulse schedule with Qiskit Dynamics for the provided Hamiltonian. Finally, plot the histogram of the results. Does that look like a useful GHZ state? We hope this motivated you to calibrate your pulses for the subsequent problems.

- Learn how to calibrate a single-qubit gate using RoughAmplitudeCal class from Qiskit Experiments [8].

- Now let's calibrate a two-qubit gate (CX gate). In the case of a two-level Hamiltonian, the only visible errors would be the AC Stark shift and quantum crosstalk. A technique called echo cross resonance can mitigate these errors. We will distribute some code to help you run this scheme. Apply this technique to optimize your CX gate.

- Run your GHZ circuit again with the optimized pulse gate and plot the histogram. Do you see any improvements?

(Note: You may want to use machine learning to optimize your pulses. That is fine but optimize your pulses for a universal gate set, instead of optimizing solely for the GHZ circuit.)

3. Zero-Noise Extrapolation (ZNE) in the case of a multi-level Hamiltonian. In quantum information, it is common to assume that there are only two states, $|0\rangle$ and $|1\rangle$. However, in real quantum systems like transmon qubits and trapped ion qubits, additional energy states exist beyond the qubit states. These extra energy states introduce new types of errors during qubit manipulation. Let's explore the impact of these states with Qiskit Dynamics. We will use a technique called Zero-Noise

Extrapolation (ZNE) [9][10]. In ZNE, varying degrees of errors are intentionally introduced by manipulating pulse lengths. Those data can then be extrapolated to compute the error-mitigated result. However, the higher energy levels introduce new types of error terms in the Hamiltonian, so you need to carefully calibrate your pulses in order to successfully mitigate the errors.

- (Task): Perform ZNE using the provided multi-level Hamiltonian. The effectiveness of ZNE will depend on the quality of your pulse calibration. Perform DRAG calibration and rotary term calibration to account for the errors. The DRAG calibration code can be found at [11][12]. You'll need to implement rotary term calibration on your own by referring to [13].

  To perform ZNE, you will [illegible]d an observable to calculate the expectation value. Observe the expectation value of ZZZ after preparing your GHZ state. (Note: Z measurement is the default measurement in Qiskit's measure() function).

  Moreover, stick to the Qiskit Dynamics simulator for this problem, as the calibration process might be time-consuming when using real quantum hardware without priority access.

References

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