FIVE QUBITS

QCSA Fall Fest 2023 Hackathon Submission Packet

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The team

1. **Ayan Kumar**

   My academic journey, fueled by a Bachelor's in Computer Engineering, combines the realms of quantum physics and computer science. With a passion for data analysis and deep learning, I honed his skills during internships, contributing insights and innovations to this dynamic field.

2. **Changsoo (Bryson) Kim**

   I am a Master's student in Computer Science deeply interested in developing a compiler for quantum computers. My current research is focused on optimizing, routing, and approximating quantum circuits.

3. **Jai Israni**

   With a Bachelor's in Engineering Physics and currently pursuing the Master of Quantum Science and Technology, I bring a unique blend of physics and engineering to the quantum realm. During my AI and quantum algorithms research internship, I delved into the intricacies of machine learning and AI. I share a deep passion for innovative technology.

4. **Rashmi Raghu**

   I'm currently pursuing a Master's in Computer science with a broad interest in technology, spanning system design, blockchain, and cryptography. I'm particularly passionate about developing quantum algorithms to enhance security and abstraction in automata. My research focus is on making systems faster and more scalable through innovative technologies.

5. **Shrey Upadhyay**

   I'm pursuing an MS in Quantum Science and Technology. Armed with a Bachelor's in Physics, I possess a strong foundation in the fundamental sciences. During my internships in quantum finance and fintech, I've worked closely in quantum technologies to explore the exciting intersections of finance and quantum mechanics.

About the project

Motivation to choose the project

We are motivated to undertake this project due to our profound interest in quantum computing and its real-world implications. Exploring the impact of pulse sequences on coherence time and circuit fidelity using Qiskit Pulse enables us to delve into the intricacies of quantum hardware and error correction. Understanding how pulse sequences affect coherence and fidelity is pivotal for constructing dependable quantum algorithms.

Furthermore, we are intrigued by the opportunity to investigate how various pulse sequences, hardware platforms, and circuit depths influence the performance of quantum systems. This research contributes to the evolution of more robust and efficient quantum computers. We've taken the initiative to elevate our project by incorporating error mitigation and correction techniques within noisy pulse sequence models, further enhancing the reliability of quantum computations.

Explanation

We worked on Qiskit Pulse by considering multiple aspects to it. We investigated the effects of different parameters on Pulse sequence that affect the coherence and overall circuit fidelity. We addressed three main things through the project. They are listed below.

- Creation of Calibrated but noisy pulse sequence systems.
- Error mitigation using Uhrig Dynamical Decoupling
- Error correction utilizing the Hamming space.

Each of these sections are elaborated in the upcoming sub-sections:

Creation of Calibrated Pulse sequences. (Noisy)

We construct a four-qubit pulse sequence employing a variety of gates, including Hadamard and Pauli's exclusion gates, among others. Subsequently, we introduce noise to the entire system via the Noise Model, with a specific focus on qubit 1, allowing us to assess the effects of Error Mitigation and Error Correction.

Pulse gates play a pivotal role in translating logical circuit gates, such as X gates, into Qiskit Pulse programs, known as Schedules. This conversion process, often referred to as calibration, seeks to achieve high fidelity. In our scenario, we achieve this fidelity by configuring the pulse schedule using a Gaussian curve, specifying parameters such as amplitude, duration, and more. To further optimize the circuit, we employ an integrated transpiler.

Here are the steps we used to create and optimize a four-qubit pulse sequence, introduce noise, and calibrate the pulse gates for a quantum computer using Qiskit:

1. **Create a Four-Qubit Pulse Sequence:**
   - Set up a quantum circuit with four qubits.
   - Apply multiple quantum gates, including Hadamard, Pauli's exclusion gates, and others to create the desired logical circuit.
2. **Introduce Noise Using the Noise Model:**
   - Import or create a noise model that describes the errors and imperfections in the quantum computer.
   - Apply the noise model to the entire quantum system.
3. **Concentrate Noise on Qubit 1 and correct a bit-flip error using Three-bit code:**
   - Adjust the noise model to concentrate noise on qubit 1.
   - This step is essential to analyze error mitigation and error correction specifically for qubit 1.
   - Three-bit code is used to correct a bit-flip error.
4. **Map Logical Gates to Pulse Gates:**
   - Define a mapping that associates logical circuit gates (e.g., X gate) with Qiskit Pulse programs called Schedules.
   - This mapping is referred to as calibration.
5. **Calibrate Pulse Gates with Gaussian Curves:**
   - Configure the pulse schedule for each gate using Gaussian curves.
   - Specify parameters such as amplitude, duration, and other relevant parameters.
   - The goal is to ensure that the calibration faithfully implements the logical operation it is mapped from (e.g., X gate calibration driving |0> to |1>).
6. **Optimize the Circuit:**
   - Use an in-built transpiler in Qiskit to optimize the quantum circuit.
   - The transpiler helps in improving the circuit's efficiency and minimizing errors.
7. **Apply post-measurement error correction:**
   - Utilize HAMMER to reconstruct the noisy output probability distribution.
   - Exploits the Hamming structure of incorrect outcomes to boost the likelihood of the correct outcomes.

Now that we have an optimized, noisy but calibrated 4 qubit pulse circuit, let’s move on to fixing the errors. As stated earlier, we can correct errors using Error mitigation, Error suppression and Error correction techniques but due to the scarcity in time, we have implemented two techniques each one for Error mitigation and Error correction for the pulse in hand. You can find the explanation in the upcoming section.

Error mitigation using Uhrig Dynamical Decoupling(UDD)

When addressing error mitigation in quantum computing systems, it's crucial to consider various techniques designed to enhance the overall reliability and accuracy of quantum computations. Among these techniques, dynamical decoupling (DD) stands out as particularly effective, and one specific sequence that has demonstrated promising results in DD is known as Uhrig's sequence. In the context of this discussion, we will delve into the application of Uhrig's sequence for mitigating errors and demonstrate how it significantly improves the outcomes of quantum computations.

Dynamical decoupling is a quantum error mitigation strategy that aims to suppress unwanted interactions between a quantum system and its environment. Uhrig's sequence, which is a modified form of a sine wave pulse, plays a pivotal role in this process. By employing Uhrig's sequence, we introduce controlled operations on the quantum states, effectively "decoupling" the qubit from its noisy surroundings. This decoupling mechanism helps protect quantum states from environmental disturbances and enhances the coherence time of the quantum system.

In practical terms, the process involves applying Uhrig's sequence to a specific qubit, typically qubit 0. Uhrig's sequence serves as a carefully designed set of quantum gates or pulses that counteract the detrimental effects of noise and decoherence on the qubit's state. As a result, the quantum system becomes more resilient and less susceptible to errors caused by factors like thermal fluctuations and electromagnetic interference.

The key insight here is that by applying Uhrig's sequence as a form of dynamical decoupling, we can observe a marked improvement in the outcomes of quantum computations. When comparing the results before and after error mitigation, it becomes evident that error rates are reduced, and the quantum system's performance is significantly enhanced. This effect is particularly pronounced in scenarios where noise and environmental factors would otherwise degrade the quality of the quantum computation.

In summary, utilizing Uhrig's sequence as a dynamical decoupling mechanism is a potent strategy to mitigate errors in quantum computing systems. By applying this carefully crafted sequence to the qubit, we can shield it from the detrimental effects of noise and environmental factors, resulting in improved quantum computation outcomes. This exemplifies the practical significance of error mitigation techniques in the realm of quantum computing, underscoring the ongoing efforts to enhance the reliability and robustness of quantum computations.

In our case, we add uhrig’s sequence on qubit 0 and add multiple duration of delays through the dynamical decoupling method. We have seen promising results through the same.

Error correction using HAMMER

Error correction is one of the most important but the hardest to tackle when we talk about Quantum systems. Through this solution, we were able to incorporate an algorithm that has great results when it comes to Error correction. Talking about the method, we employed a three-step approach:

1. *Identifying Hamming Distance Neighborhoods:* For each unique outcome in the histogram, we calculated the Hamming distance neighborhood, effectively quantifying how "close" these outcomes are to one another in terms of bit flips.

2. *Analyzing Neighborhood Scores:* We assigned weights to these neighborhoods based on their scores, considering factors like proximity to the correct answer and other relevant metrics.

3. *Computing Effective Values:* Utilizing the assigned weights and the probability distribution of the neighborhood, we computed the effective value for each outcome in the probability distribution. This allowed us to give greater importance to outcomes with higher fidelity and relevance.

This approach was aimed at improving the resilience of quantum computations to incorrect outcomes that are Hamming-space neighbors of the correct results. By assigning and using weights effectively, it was possible to mitigate the impact of these incorrect answers and enhance the overall circuit fidelity, making quantum algorithms more reliable. This unique application of Qiskit Pulse contributed to the ongoing efforts to make quantum computing more robust and applicable to real-world problems.

On an ending note, The project revolved around addressing the issue of dominant incorrect outcomes in quantum computation that are close to the correct answers in Hamming space, which can significantly impact the reliability of quantum algorithms. Through multiple techniques mentioned above, we were able to enhance the results in the pulse circuit. In the future, we plan to work on more promising algorithms to better the efficiency of quantum algorithms.

Link to the Project

You can access the working model here.
https://colab.research.google.com/drive/1-dQrKS4DXbefJ46H1ht10p1UryNH6hRv?usp=sharing

The model is self explanatory. You will see comments to explain each portion of the code.

Feel free to reach out to us if you have any questions.