QCHack Report

IBM Technical Challenge

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1 Problem, Motivation, and Initial Plans

Our team focused on the IBM Technical Challenge. The majority of our team were interested in learning more about implementation of quantum gates using PULSE which made the challenge appealing for us. Since, the challenge asked for us to explore higher level energy states, we formulated our initial plan as follows:

Input: A parameter d, which parameterizes the number of energy levels of our qudit system.
Output:

1. A qudit system with d energy levels.
2. A proof of concept unitary operator that acts on this qudit (most likely the amplitude swap or phase flip operation equivalent on this qudit system).
3. The corresponding Pulse program that models the action of this operator. (The final deliverable)

2 Challenges faced

1. **Lack of coffee** and an **absolute lack of food**.

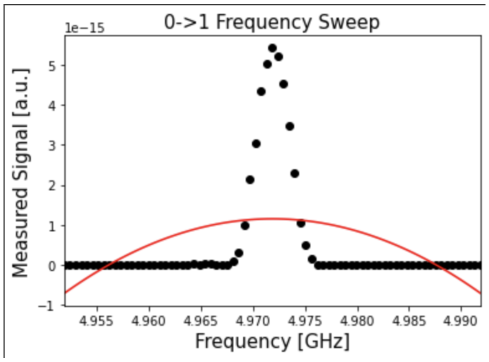

Figure 1: Failed curve fitting for frequency sweeps for 0→1 transition run on the FakeArmonk backend.

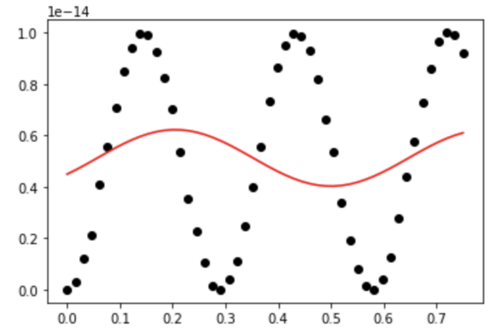

Figure 2: Failed curve fitting for amplitude sweeps for 0→1 transition run on the FakeArmonk backend.

2. Since it was not immediately clear how to extend the pulse level instructions to qudits, as the challenge proceeded, we realized that we might have set ourselves a rather ambitious goal in aiming to build an adaptable working script for a variable number of dimensions. Added to this was that the chances to run our code and thus test and debug it were few and far between due to the long waiting queues for the physical backends. Upon assessing the situation, our team quickly decided to stick to 3 levels for this challenge and implement a qutrit system.

3. Fake backends were not working correctly. We initially tried to run our code on FakeArmonk as we wanted to test and debug our code on local simulators before running it on actual backends. After spending some hours trying to make pulse calibration work on the simulator, we eventually realized that the implementation of pulse on these systems was not ideal. We also tried to run our code on other Fake backends, including insert names here but were met with the same problems. Finally, we had to resort to run most of our code on the physical backend.

4. As we had to share the cloud machine with our fellow hackers and the vast community of research pioneers utilizing IBM's back-end systems, we had to be very careful with time management. We had to find ingenious ways to convert the long waiting times required running scripts into productive brainstorming sessions.

5. We were not satisfied with the accuracy score of the Linear Discriminant Analysis classifier for the 0-1-2 discrimination. To this end, we tested out multiple classifiers like the Quadratic Discriminant Analysis classifier, SVC (from scikit learn), which performs C-Support Vector Classification, and various classifier models belonging to the Multi-Layer Perceptron Classifier family. We obtained our best accuracy using the LBFGS optimizer, with ReLU activation and two hidden layers.

3 Our Work

3.1 Using pulse to calibrate qbit states

The first step in starting our work with pulse was to setup and calibrate out pulses for a specific qbit. We started by calibrating out pulses to the qbit of FakeArmonk backend but soon realised that the pulse implementation in backend simulators was not ideal(see figs-1,2). Thus, we subsequently moved out workflow to the physical Armonk backend and started with calibrating our pulses frequency and amplitude using frequency sweeps and amplitude sweep for Rabi pi pulses. The level one measurements in the Q-I phase space are then discriminated into 0 and 1 measurement(see fig-9).

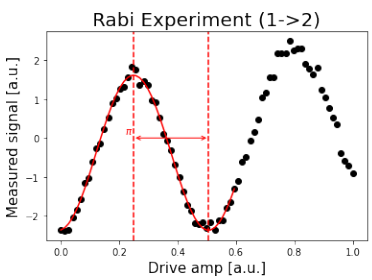

Figure 3: Curve fitting for Rabi Experiment of 1->2 transition

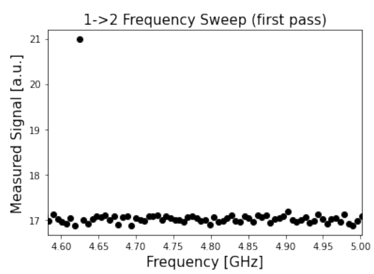

Figure 4: First pass of the Frequency Sweep for 1->2 transition

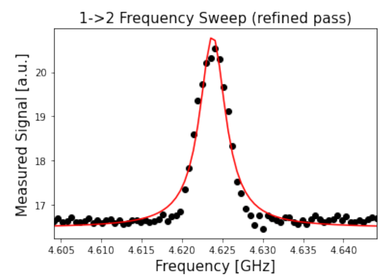

Figure 5: Curve fitting for refined pass of the Frequency Sweep for 1->2 transition

3.2 Using pulse to calibrate qutrit states

The next step in working towards our goal is to calibrate the pi pulse for the transition from level $1 \rightarrow 2$. This is done using a two level frequency sweeps around $400Mhz$ below the resonant frequency for the $0 \rightarrow 1$ transition. The amplitude is obtained using a sweep similar to the $0 \rightarrow 1$ transition. The level one measurements in the Q-I phase space are then discriminated into 0 and 1 measurement(see fig-8).

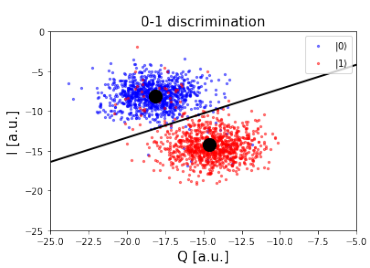

Figure 6: A good 0-1 IQ plot leading to a clean discrimination

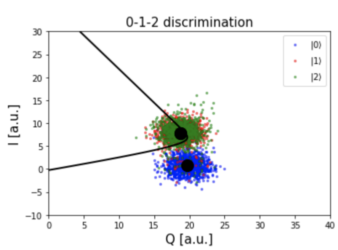

Figure 7: A bad 0-1-2 IQ plot leading to an unclean discrimination

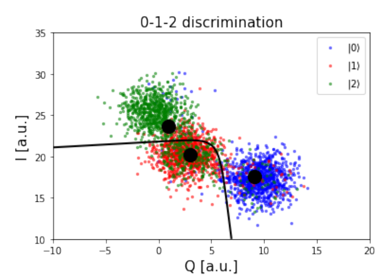

Figure 8: A good 0-1-2 IQ plot leading to a clear discrimination.

3.3 Discriminant Analysis

We tested multiple classifier models like LinearSVCs, and SVCs along with the models we list below. The best performing classifier was the Multi-Layer Perceptron classifier with the following attributes:

1. We used two hidden layers of 100 perceptrons each.

2. We used the LBFGS optimizer, which is a quasi-Newton optimization method. The advantage is that it uses limited memory, which gives fast convergence times.

3. We used the Rectified Linear Unit as an activation function. Being an extremely simple non-linear function it has the advantage of both evaluating blazingly fast and being able to approximate a variety of functions without suffering from barren plateau issues of the sigmoid or tanh activation functions.

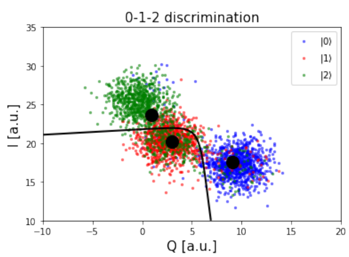

Figure 9: Using the LDA classifier we achieve a score of 0.8144

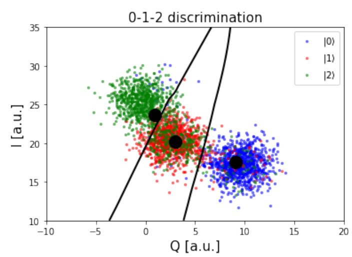

Figure 10: Using the QDA classifier we achieve a score of 0.8222

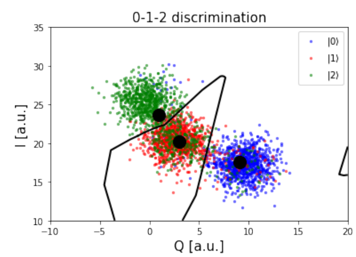

Figure 11: Using the MLP classifier we achieve a score of 0.8399

3.4 Implementing Local Hadamard Gates and Some X like Gates

In this project, we also introduce a small set of gates that include local Hadamard gates and some X like gates for the qtrit system. A local Hadamard gate H_{ij} acts on a qtrit state such that the resultant state is an equal superposition of $|i\rangle$ and $|j\rangle$ basis states if the initial state is $|i\rangle$ or $|j\rangle$ else the initial state remains undisturbed. As for the X like gates, these gates can be perceived as permutations among the amplitudes of the states $|0\rangle, |1\rangle$ and $|2\rangle$. We implement these gates using the currently available pulse instructions. Along with introducing these gates, we also show a proof of concept of how these gates act on the qtrit states by running experiments on IBMQ Armonk.

4 Future Work/Implications

As we worked on the challenge, out team constantly brainstormed to appreciate the implications and research potential of the project undertaken by us.

One of the potential uses that caught our attention was the usefulness of using qudrit systems in simulation physical system that are naturally described in Hilbert spaces of dimensions greater than 2. One such system that immediately caught our eye is particles with spins higher than 1/2. For example, studying the dynamics of a system with spin (s = 1) in a magnetic field is much more natural using qutrits.

Future course for the project could include defining a more robust set of gates for the qutrit systems along with generalizing the process for dimension greater than 3.

Also, as is known that the excitation energy gap between exited states decreases with increasing quantum number for transmon qubits, it will be interesting to verify experimentally the upper limit for the dimensions for which a qudit state can be obtained before the physical limitation of limited resolution kicks in. This will be especially interesting in the realm when the approximation for the hamiltonian contribution from the non-linear Josephson junction breaks down.