Project Report (Quantum Computation, Problem-2)

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1 Problem Statement

Current quantum devices are noisy, and are not yet capable of applying error correction techniques. Therefore, various mitigation techniques have been proposed in literature which try to lower the effect of error on the system. In this project we shall look into one such technique to mitigate the effect of noise on idle qubits. In general, when storing a qubit $\rho = |\psi\rangle\langle\psi|$ (in density matrix notation), where $|\psi\rangle = cos(\frac{\theta}{2})|0\rangle + sin(\frac{\theta}{2})|1\rangle$, it is subjected to errors on the channel E, leading to an erroneous state ρ_{noise}. From the method of unitary padding mentioned in [Mas+22], we pad unitary operators U and V before and after ρ, respectively. The output state is now $\rho_{out} = VE(U\rho U^{\dagger})V^{\dagger}$. Our goal is to find optimized U and V such that the fidelity $\mathcal{F} = \langle\psi|\rho_{out}|\psi\rangle$ is maximized. The necessary criteria is $\langle\psi|\rho_{out}|\psi\rangle \geq \langle\psi|\rho_{noisy}|\psi\rangle$. For the sake of simplicity we will define the fidelity as follows

$$\mathcal{F} = \Big\{ \sum_{s\in\{0,1\}^n} \sqrt{p_{in}(s).p_{out}(s)} \Big\}^2$$

where n is the number of qubits we are incorporating in our circuit, and, p_{in} and p_{out} are the probability distribution of the states ρ and ρ_{out}, respectively. In this project, we investigated the following things:-

1. Given the structures of the unitary operators U and V proposed in [Mas+22], what would the optimum angle be for the R_y gate for the different types of noise channels given in [Mas+22] [which are *Depolarization noise, Biased Pauli noise (Dephasing noise), Thermal Relaxation noise (Amplitude Damping noise)*].

2. Along with using the R_y gate, we also tried using the R_x and R_z gate.

3. We increased the number of qubits in the circuit, and checked whether at any point the extra $CNOT$ gates would incur more noise, in contrast to, not using any sort of padding, i.e., would this method lead to extra error being introduced to the state.

2 Results

2.1 Depolarization Noise

For Depolarization noise, we saw that as the number of qubits increased, with the increment of probability of error (p_{err}), fidelity decreased with a higher rate of decay (which seemed to be exponential). Also, as the number of qubits increased, we didn't notice any difference between the fidelity distribution while using the $U - V$ padding, and the fidelity distribution while not using any sort of padding. We also performed the whole experiment using the R_x and R_z gate in place of the usual R_y gate, but we didn't notice any improvements in the result.

2.2 Dephasing Noise

For Dephasing noise, we can see that as the number of qubits increased, with the increment of probability of error (p_{err}), and the bias (b), fidelity decreased with a higher rate of decay (which seemed to be exponential). Also, as the number of qubits increased, we didn't notice any difference between the fidelity distribution while using the $U - V$ padding, and the fidelity distribution while not using any sort of padding. We also performed the whole experiment using the R_x and R_z gate in place of the usual R_y gate, but we didn't notice any improvements in the result.

2.3 Amplitude Damping Noise (Thermal Relaxation Noise)

For Amplitude Damping noise (or Thermal Relaxation noise), we did notice that while using the R_y gate, upon increasing the number of qubits, we get a random pattern implying that using R_y gate in the circuit doesn't help much to capture the noise pattern in the circuit, with respect to delay in the circuit. On the other hand, upon using the R_x and R_z gate, we saw that as the delay increased, the fidelity decreased at an exponential rate.

All the detailed results can be seen in the notebook that we have shared.

3 Final Conclusion

Using the R_y gate in the padding unitaries U and V, we were able to capture the noise patterns for the Depolarization noise model and the Dephasing noise model, but not for Thermal Relaxation noise model. But using the R_x and R_z gate, we were able to capture the noise pattern of all the different noise models mentioned above, although, the R_x and R_z gate didn't show much difference in their ability to capture the noise pattern in the aforementioned noise models.

References

[Mas+22] Alena S. Mastiukova et al. *Suppressing decoherence in noisy intermediate-scale quantum processors with unitary operations*. 2022. DOI: 10.48550/ARXIV.2208.04926. URL: https://arxiv.org/abs/2208.04926.