readout error mitigation

OVERHEAD BENCHMARKING PIPELINE FOR QUANTUM ERROR MITIGATION

ELLA CARLANDER, RUHEE NIRODI, ALEXANDROS PELTEKIS

Background & Motivation

In the noisy intermediate-scale quantum (NISQ) era, computation on quantum devices is unreliable due to noise.Quantum error mitigation (QEM) is an active field seeking to reduce these effects, and has produced many techniques that vary in performance and resource requirements. Unitary Fund has developed Mitiq, an open-source toolkit for easily implementing QEM techniques [1].

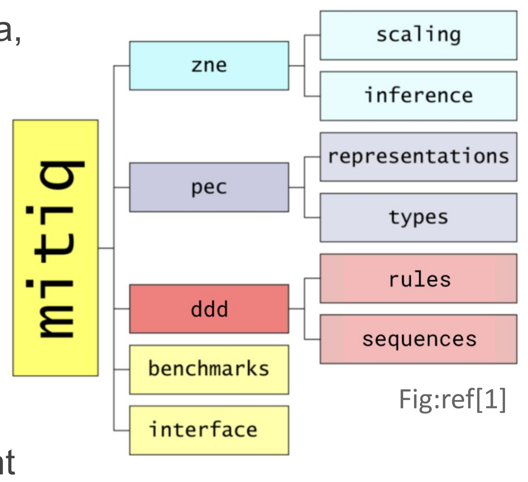


Fig:ref[1]

Mitiq does not currently address how their mitigation implementations vary in overhead. Individuals seeking to perform QEM may have different priorities regarding the consumption of resources and performance improvement. This motivates the need for a tool that can characterize and compare the overhead of these techniques, providing insight into which method may best suit one's needs. This establishes the context of our project, where we produce an analysis pipeline and GUI that allow users to easily evaluate and compare Mitiq's existing QEM implementations.

Overhead & Benchmarking Circuits

Overhead refers to the additional resources required to implement QEM techniques. Assessing overhead is crucial for understanding the trade-offs between performance improvement and resource consumption. In this project, we characterized overhead using three measures:

1. **Added circuit depth -** measures the number of non-concurrent operations
2. **Additional gate counts** - distinguishes between single-qubit and two-qubit gates
3. **Additional time -** time required to run the circuits with QEM techniques vs without

For comparing QEM methods, we use benchmarking circuits, which evaluate the performance and overhead of QEM techniques through standardized tests. Specifically, we have used **mirror circuits** [4], quantum circuits with multiple reflection and inversion layers], as shown in the figure to the right..

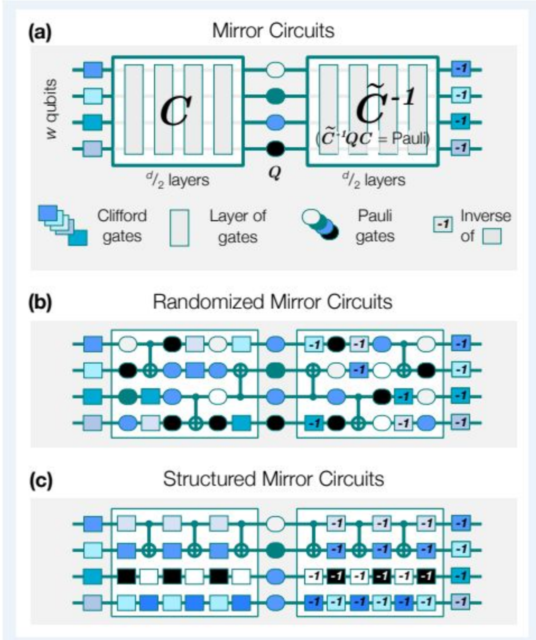


Fig:ref[4]

Thermal & Depolarizing Noise Channels

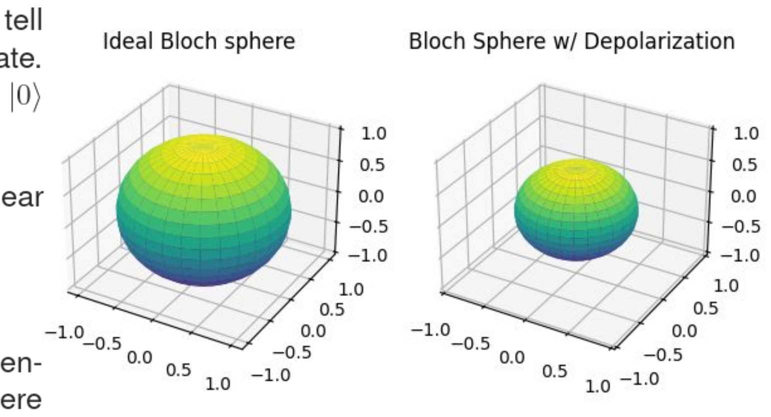
We evaluated how effective different QEM techniques were at mitigating two types of quantum noise [5]:

1.Thermal Relaxation: Described by the parameters T_1 and T_2 which tell us how quickly a quantum system returns to its equilibrium (thermal) state. Specifically, T_1 describes the decay time of a qubit's state from $|1\rangle$ to $|0\rangle$ (qubit lifetime), and T_2 describes the qubit phase coherence.

2.Depolarization: A d-dimensional model that maps a state ρ into a linear combination of of itself and the maximally mixed state,

$$\epsilon(\rho) = \frac{pI}{d}(1-p)\rho$$

Here, p is the probability that the qubit is depolarized, and d is the dimension (2 for a single qubit system). Depolarization causes the Bloch sphere to contract radially inwards, as shown in the graph to the right.



Error Mitigation Techniques

Digital Dynamical Decoupling

Dynamical Decoupling (DD) is a QEM technique that preserves quantum coherence by applying a sequence of carefully timed and designed pulses to the system to counteract the effects of environmental noise [2]. These pulses effectively average out the noise over time, preventing decoherence of quantum states. In Digital DD, sequences of DD pulses can be mapped to sequences of discrete quantum gates, typically Pauli gates. Mitiq contains three commonly used pulsing sequences, indicated as rules in the plot [3].

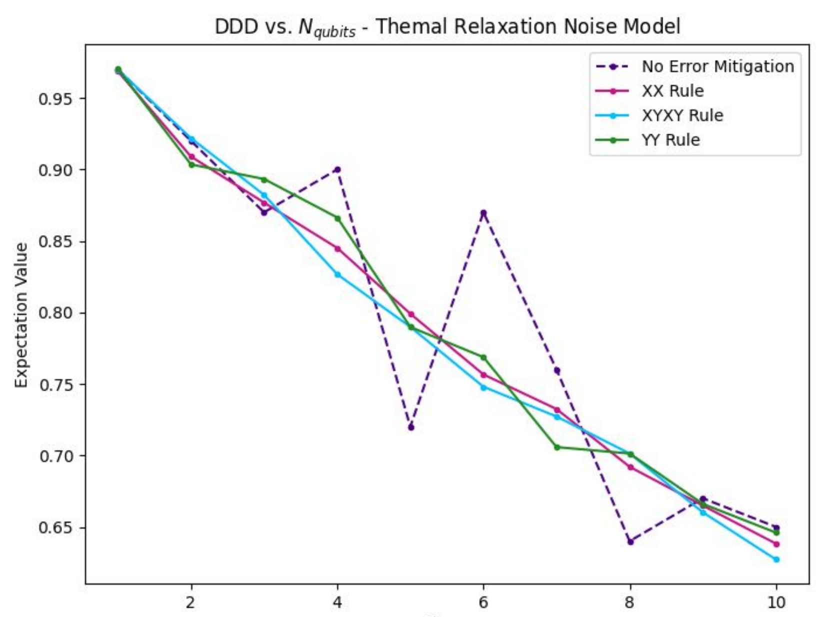


Figure: Here, we construct mirror circuits with 20 reflection layers with increasing number of qubits (1-10). We then run DDD on each circuit using the three different rules, or pulsing sequences, that Mitiq offers (XX, XYXY, and YY, where names correspond to the string of Pauli operators used as digital pulses). We used a thermal relaxation noise model with readout error set to 2.5% for all measurements

Readout Error Mitigation

Readout error mitigation (REM) mitigates errors that occur during the measurement stage. It characterizes readout errors by performing measurements on known quantum states (such as computational basis states) and then uses this information to correct the measurement results obtained during the execution stage [2]. All of the overhead in REM comes from the noise characterization stage, which only needs to be done once for a specific backend or quantum system. Therefore, overhead for REM is independent of the circuit run, and has a one-time cost [3].

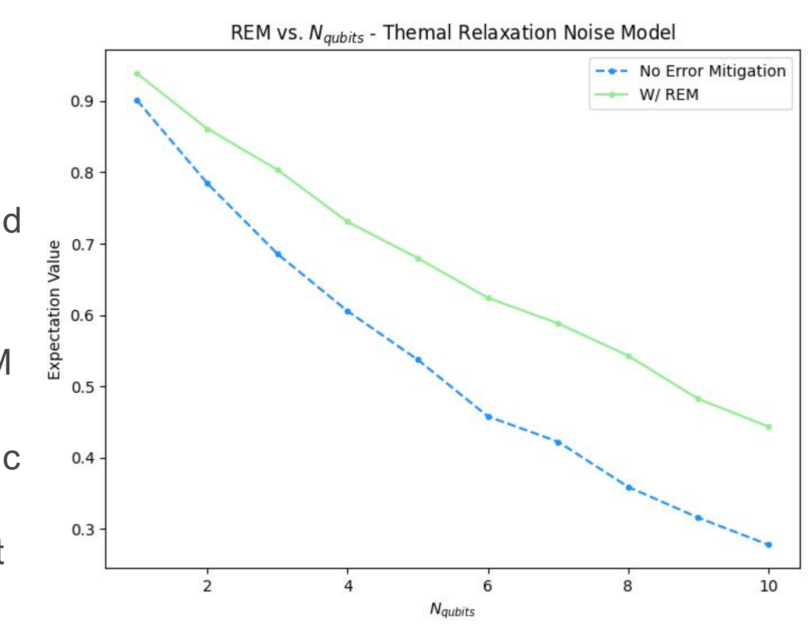


Figure: We use a thermal relaxation noise model with readout error set to 2.5% for all measurements. REM noise characterization is then applied to this noisy simulator, where we incur our one-time overhead costs. We again sweep over N_qubits, fixing the layer depth of each mirror circuit at 20, and measure expectation values pre and post applying REM.

Zero Noise Extrapolation

Zero Noise Extrapolation (ZNE) is a hybrid quantum-classical technique. It runs quantum circuits with increasing noise levels, extracts an expectation value for each, and then uses classical fitting to extrapolate to what the ideal expectation value would be in a noiseless environment. In Mitiq's implementation of ZNE there are two relevant classical variables, (1) the type of extrapolation or fitting used to find the y-intercept (ideal expectation value) and (2) the noise scaling values, which determine how the noise grows in each additional circuit that is run [3].

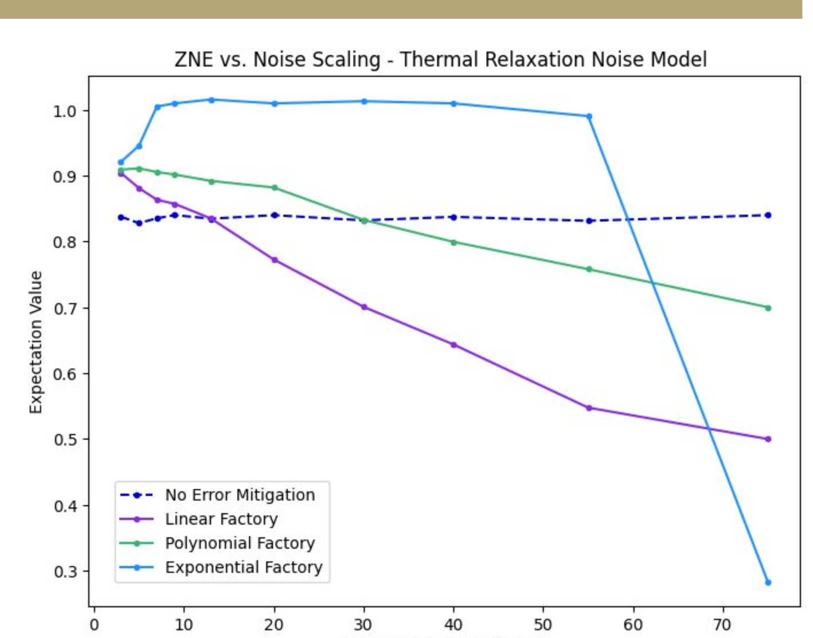


Figure: Here, we construct a mirror circuit with N_qubits = 4, and 20 reflection layers. We then evaluate ZNE for 3 different classical extrapolation techniques: a linear extrapolation method, a polynomial method of order 2, and exponential. We then sweep over the noise scaling parameters (each of which is a linearly spaced array of noise values. For example '5' corresponds to the array noise scaling values = [1,2,3,4,5])

Probabilistic Error Cancellation

Probabilistic Error Cancellation (PEC) is QEM technique in which ideal operations in a circuit are represented as linear combinations of noisy operations. Different implementable circuits are then sampled from the quasi-probability representation of the ideal input circuit. The ideal expectation value is then approximated using a suitable linear combination of the noisy expectation values from these sampled circuits. In Mitiq's implementation, the number of circuits sampled is an input parameter that influences both overhead and performance [3].

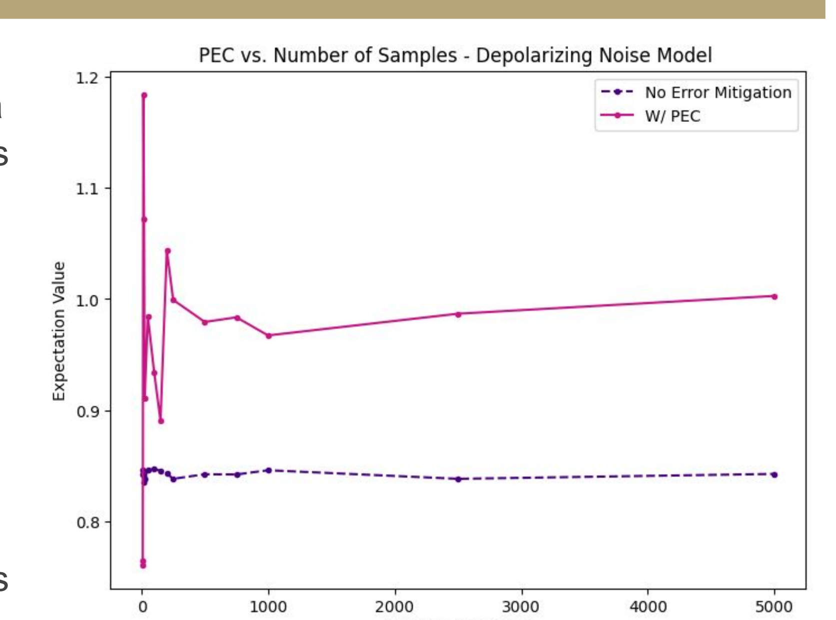


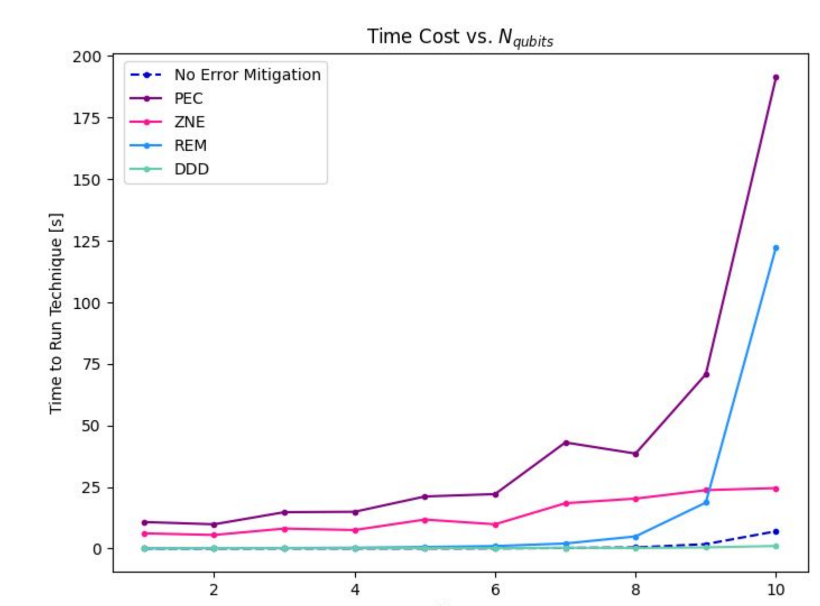
Figure: Again, we construct a mirror circuit with N_qubits = 4, and 20 reflection layers. We then evaluate PEC performance as we sweep over the number of circuits sampled. PEC best mitigates depolarizing noise, so we created a depolarizing noise model with single qubit instruction errors of 0.5% and 2-qubit instruction errors of 2.5%.

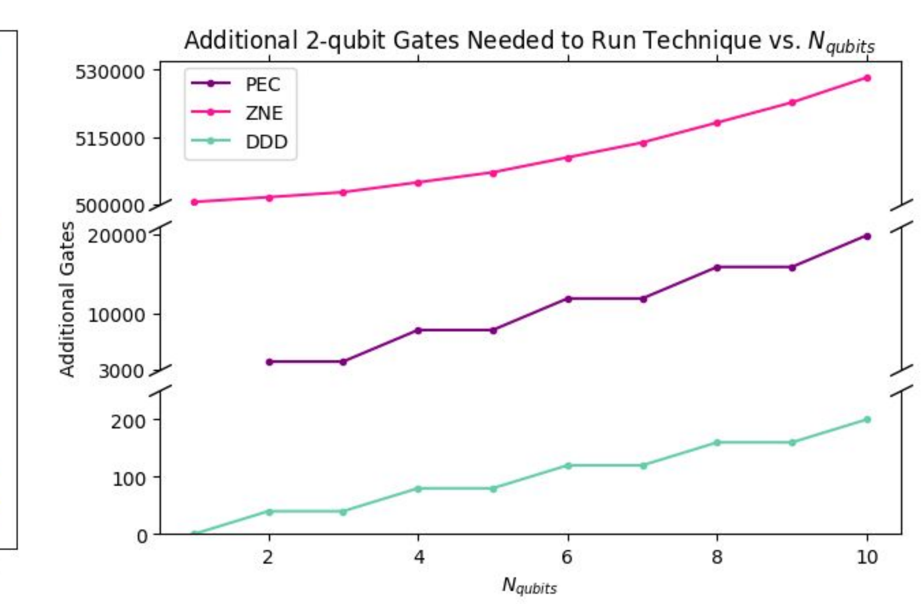
Results

The overarching goal of this project is to directly compare the resources needed to run each QEM technique to find the trade-off between efficiency and successful error mitigation. We thus want to run a sweep over the number of qubits in our input mirror circuits for each technique, with parameters corresponding to each one's most successful QEM performance. We chose:

- **DDD:** YY rule
- **ZNE:** exponential extrapolation method with 7 scaling factors
- **PEC:** number of samples = 100

We also standardized our noise models between techniques, choosing depolarizing errors that gave us roughly the same pre-mitigation expectation values as our thermal relaxation model. We compare the incurred time costs and number of additional two qubit gates needed to run each technique.





Future Work, References, and Acknowledgments

In the future, we would like to see this analysis pipeline extended to include every QEM technique that Mitiq has an implementation for, as well as integrating them with actual quantum hardware.

References

1. LaRose, R., Mari, A., Kaiser, S., Karalekas, P. J., Alves, A. A., Czarnik, P., ... & Zeng, W. J. (2022). Mitiq: A software package for error mitigation on noisy quantum computers. Quantum, 6, 774.
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