Locality and Error Mitigation of Quantum Circuits

Quantum Wednesday

Nate Stemen

Apr 19, 2023

Today's Paper

Locality and Error Mitigation of Quantum Circuits

Minh C. Tran,[1] Kunal Sharma,[1] and Kristan Temme[1]

[1] *IBM Quantum, IBM T.J. Watson Research Center, Yorktown Heights, NY 10598, USA*

(Dated: March 14, 2023)

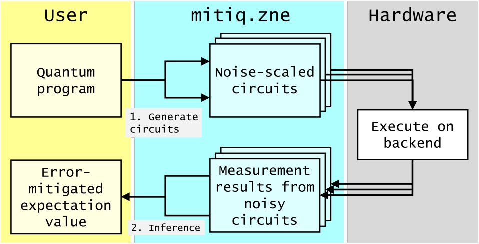
In this work, we study and improve two leading error mitigation techniques, namely Probabilistic Error Cancellation (PEC) and Zero-Noise Extrapolation (ZNE), for estimating the expectation value of local observables. For PEC, we introduce a new estimator that takes into account the light cone of the unitary circuit with respect to a target local observable. Given a fixed error tolerance, the sampling overhead for the new estimator can be several orders of magnitude smaller than the standard PEC estimators. For ZNE, we also use light-cone arguments to establish an error bound that closely captures the behavior of the bias that remains after extrapolation.

https://arxiv.org/abs/2303.06496

Zero-Noise Extrapolation

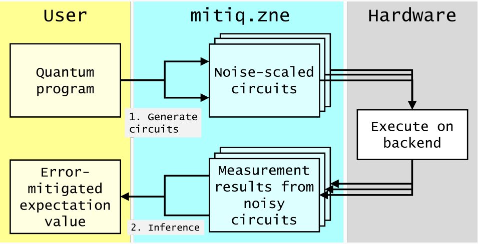
[1] McDonough et al., "Automated quantum error mitigation based on probabilistic error reduction".
[2] Temme, Bravyi, and Gambetta, "Error Mitigation for Short-Depth Quantum Circuits".

Zero-Noise Extrapolation



[1]McDonough et al., "Automated quantum error mitigation based on probabilistic error reduction".
[2]Temme, Bravyi, and Gambetta, "Error Mitigation for Short-Depth Quantum Circuits".

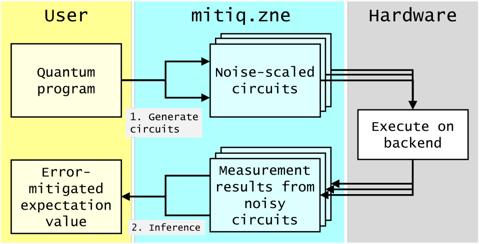
Zero-Noise Extrapolation



- $\langle A(\lambda)\rangle = \mathrm{tr}[A\rho(\lambda)]$
- biased estimator, but *no knowledge* of noise model needed
- error bounded by (Richardson) extrapolation error

[1] McDonough et al., "Automated quantum error mitigation based on probabilistic error reduction".
[2] Temme, Bravyi, and Gambetta, "Error Mitigation for Short-Depth Quantum Circuits".

Zero-Noise Extrapolation



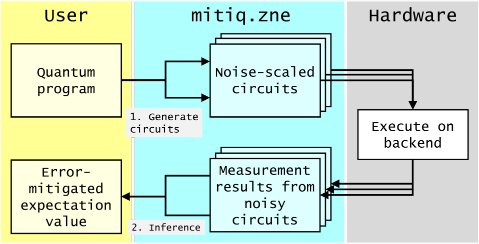
- $\langle A(\lambda)\rangle = \mathrm{tr}[A\rho(\lambda)]$
- biased estimator, but *no knowledge* of noise model needed
- error bounded by (Richardson) extrapolation error

Probabilistic Error Cancellation

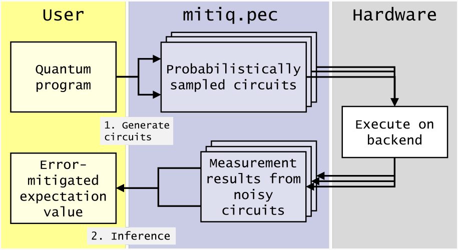
[1] McDonough et al., "Automated quantum error mitigation based on probabilistic error reduction".
[2] Temme, Bravyi, and Gambetta, "Error Mitigation for Short-Depth Quantum Circuits".

Review[2]

Zero-Noise Extrapolation



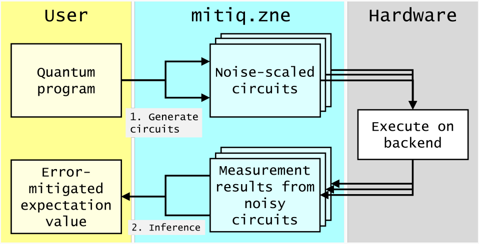
Probabilistic Error Cancellation



- $\langle A(\lambda)\rangle = \mathrm{tr}[A\rho(\lambda)]$
- biased estimator, but *no knowledge* of noise model needed
- error bounded by (Richardson) extrapolation error

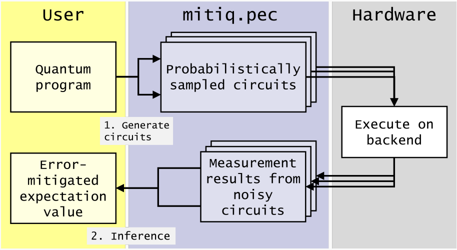
[1] McDonough et al., "Automated quantum error mitigation based on probabilistic error reduction".
[2] Temme, Bravyi, and Gambetta, "Error Mitigation for Short-Depth Quantum Circuits".

Zero-Noise Extrapolation



- $\langle A(\lambda)\rangle = \mathrm{tr}[A\rho(\lambda)]$
- biased estimator, but *no knowledge* of noise model needed
- error bounded by (Richardson) extrapolation error

Probabilistic Error Cancellation



- $\langle A\rangle = \mathrm{tr}[A\mathcal{U}(\rho)] = \sum_{\vec{\alpha}} \eta_{\vec{\alpha}} \langle A_{\vec{\alpha}}\rangle_{\text{noisy}}$
- *unbiased* estimator, but requires detailed knowledge of noise model
- more efficient methods exist[1]

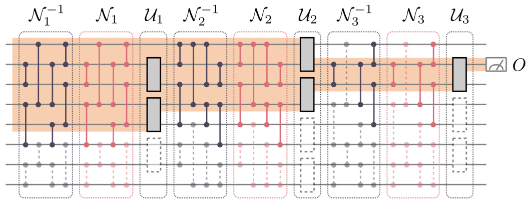
[1] McDonough et al., "Automated quantum error mitigation based on probabilistic error reduction".
[2] Temme, Bravyi, and Gambetta, "Error Mitigation for Short-Depth Quantum Circuits".

Key Concepts

Local Observable

1. An *observable* is a thing that we can design an experiment to measure.
2. Mathematically, this means a self-adjoint, or Hermitian, operator $A = A^\dagger$.
3. **Local** means A is supported one a subset of the quantum systems at hand.
4. Examples:

Light Cone

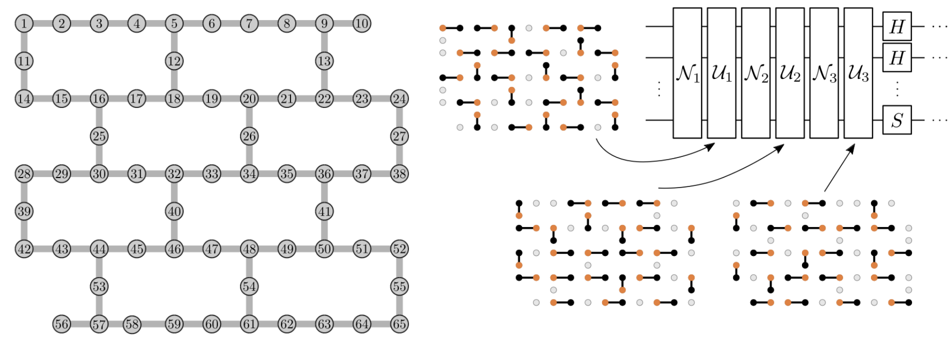


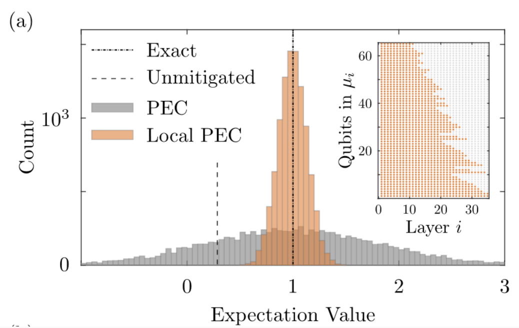
1. something else

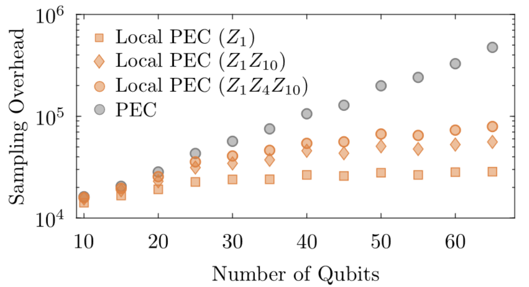
Assumptions

1.

Numerical Results




(a)
Exact
Unmitigated
PEC
Local PEC
Count
10^3
0
0
1
2
3
Expectation Value
Qubits in μ_i
60
40
20
0
10
20
30
Layer i


Local PEC (Z_1)
Local PEC ($Z_1 Z_{10}$)
Local PEC ($Z_1 Z_4 Z_{10}$)
PEC
Sampling Overhead
10^6
10^5
10^4
10
20
30
40
50
60
Number of Qubits

Results

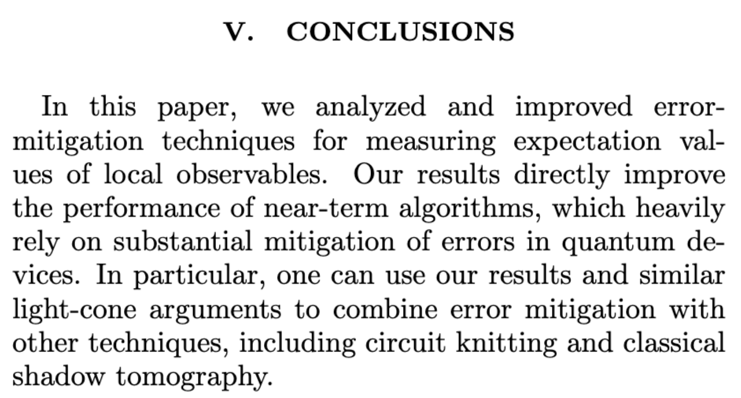
$$\hat{o}_z^{\mathsf{LoPEC}}(\boldsymbol{\sigma}) \stackrel{\mathsf{def}}{=} o_z(\boldsymbol{\sigma}) \prod_{(i,j)\in\mu} \gamma_{i,j}\sigma_{i,j}$$

$$\mathrm{Var}\left[\hat{o}_z^{\mathsf{LoPEC}}\right] = \mathcal{O}\left(\exp\left[4\sum_{(i,j)\in\mu} \lambda_{i,j}\right]\right)$$

Do we want these techniques in Mitiq?

1. Does this slot into our existing `execute_with_pec` function?
2. How does this perform as an observable O go from local to “unlocal”.

and then...



V. CONCLUSIONS

In this paper, we analyzed and improved error-mitigation techniques for measuring expectation values of local observables. Our results directly improve the performance of near-term algorithms, which heavily rely on substantial mitigation of errors in quantum devices. In particular, one can use our results and similar light-cone arguments to combine error mitigation with other techniques, including circuit knitting and classical shadow tomography.

Thank you!