Testing platform-independent quantum error mitigation on noisy quantum computers

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Introduction

Problem: Quantum computers are susceptible to environmental noise.

QEM: Quantum error mitigation (QEM) is accessible today to deal with noise.

In this work, we:

- Run experiments on hardware and apply QEM.
- Analyze how these techniques perform on different devices.

Experimental setting

Unmitigated: Evaluation of an unmitigated expectation value A' is a *trial*. Perform t trials $A'_{[1]}, \ldots, A'_{[t]}$. Quantify the estimation error via the root-mean-square error (RMSE)

$$\sqrt{\frac{1}{t}\sum_{i=1}^{t}\left(A'_{[i]} - A\right)^2}.$$

Mitigated: Evaluation of A_{QEM} as a *QEM trial*. Perform t QEM trials $A_{\mathrm{QEM}}^{[1]}, \ldots, A_{\mathrm{QEM}}^{[t]}$ and evaluate RMSE

$$\sqrt{\frac{1}{t}\sum_{i=1}^{t}\left(A_{\mathrm{QEM}}^{[i]} - A\right)^2}.$$

Quantum error mitigation

ZNE: We evaluate $k_{\mathrm{ZNE}} = 3$ noisy expectation values $A'(\lambda_i)$ at different noise scale factors $\lambda_i \in \{1, 2, 3\}$. Zero noise limit is obtained as:

$$A_{\mathrm{ZNE}} = \sum_{i=1}^{k_{\mathrm{ZNE}}} \eta_i A'(\lambda_i)$$

We consider both *linear* and *Richardson* extrapolation. The best fit coefficients η_i are

ZNE(L): Obtained from a linear best fit and depend on the noise scale factors.

ZNE(R): Obtained by

$$\eta_i := \prod_{j \neq i} \frac{\lambda_j}{\lambda_j - \lambda_i}.$$

PEC: Characterize set of noisy, implementable operations $\{\mathcal{O}_\alpha\}$ of a computer so we can represent the ideal operations $\{\mathcal{G}_i\}$ of a circuit in this basis

$$\mathcal{G}_i = \sum_\alpha \eta_{i,\alpha} \mathcal{O}_\alpha.$$

Symbols $\mathcal{G}_i$ and $\mathcal{O}_\alpha$ stand for super-operators acting on the quantum state of the qubits as linear quantum channels, and $\eta_{i,\alpha} \in \mathbb{R}$.

Methodology Overview

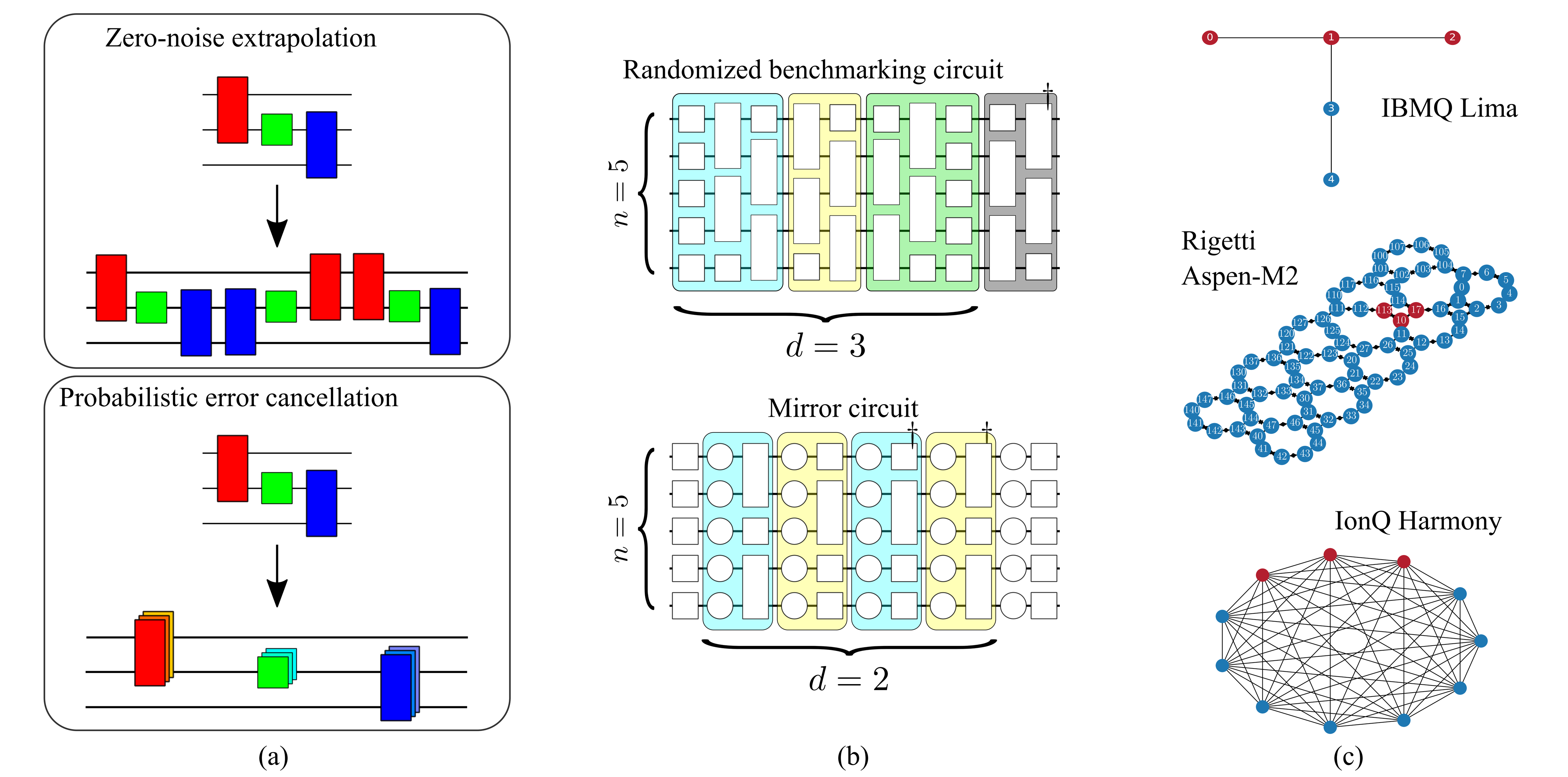

Figure 1: An overview of our method to assess the performance of quantum error mitigation in practice. An experiment consists of **(a)** a QEM technique, **(b)** a benchmark problem, and **(c)** a quantum computer

Improvement factor

Improvement factor: Quantify the performance of quantum error mitigation:

$$\mu_{\mathrm{QEM}} := \frac{\sqrt{N \sum_{C \in \mathcal{C}, \hat{A} \in \hat{\mathcal{A}}} \sum_{i=1}^{t} (A'_{[i]} - A)^2}}{\sqrt{N_{\mathrm{QEM}} \sum_{C \in \mathcal{C}, \hat{A} \in \hat{\mathcal{A}}} \sum_{i=1}^{t} (A_{\mathrm{QEM}}^{[i]} - A)^2}}$$

the circuit C is implicit in the expectation values A, $A'_{[i]}$, and $A_{\mathrm{QEM}}^{[i]}$, e.g. $A = \mathrm{tr}[C|0\rangle\langle 0|C^\dagger \hat{A}]$.

Results: Applied ZNE(L), ZNE(R), and PEC to RB circuit and mirror circuit benchmarks on IBM, IonQ, and Rigetti quantum computers. For each of these experiments, we compute the improvement factor.

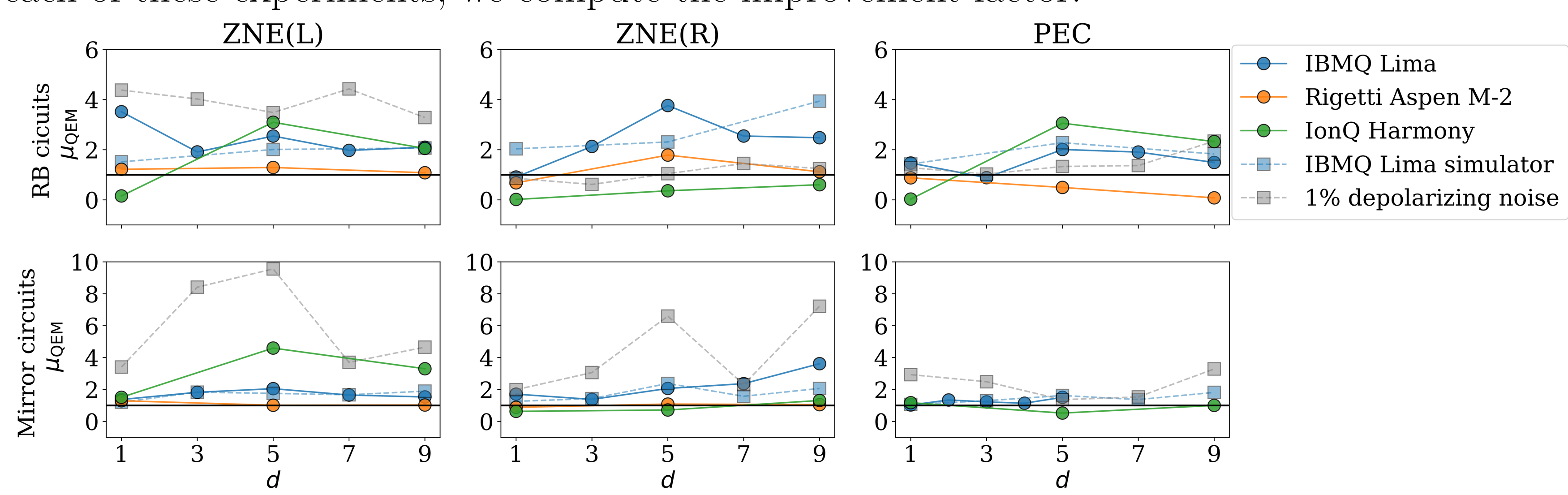

Figure 2: Improvement factor results for $n = 3$ qubit experiments.

Results

Applying ZNR(R) to $n = 3$ qubit RB circuits of various depths on IBMQ Lima.

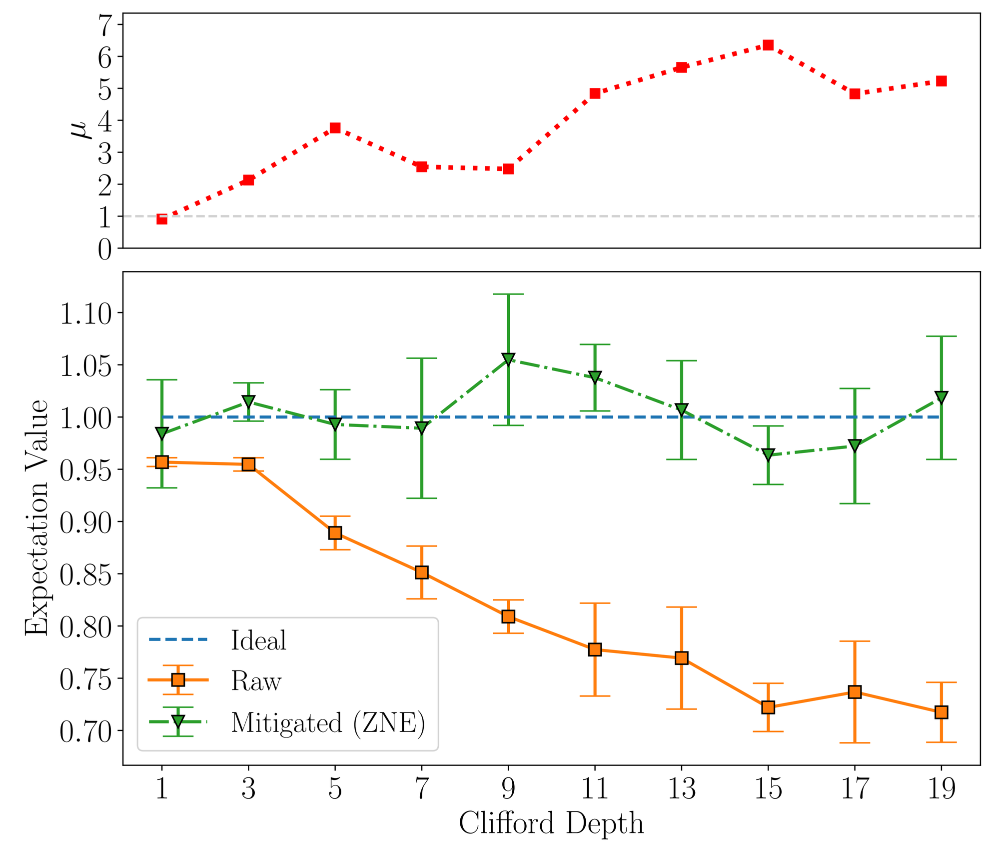

Figure 3: (Bottom panel) Unmitigated expectation values (orange squares) and corresponding mitigated expectation values using ZNE(R) (green triangles) for $n = 3$ qubit RB circuits executed on IBMQ Lima. Ideal expectation value is equal to 1 (dotted line). (Top panel) Improvement factor at each depth.

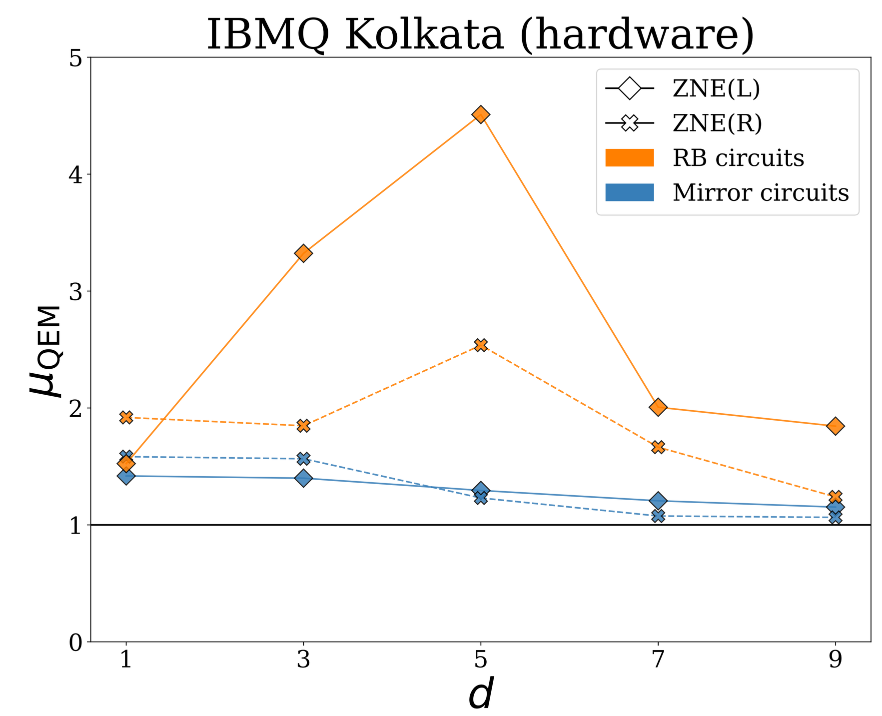

Figure 4: Improvement factor results for n = 12 qubit experiments on IBMQ Kolkata device.

Software

We implemented our experiments in Python 3.9 using version 0.18.0 of the Mitiq module to apply the ZNE and PEC techniques. Code is accessible on GitHub [https://github.com/unitaryfund/research/].