Volumetric Benchmarking of Error Mitigation with Qermit

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Motivation

The detrimental effect of noise accumulates as quantum computers grow in size, limiting applications on quantum hardware. Error-mitigation aims to reduce the error of approximations of quantities of concern, such as observable expectation values. However, it is as yet unclear which circuit types, and devices of which characteristics, benefit most from error-mitigation. We introduce volumetric benchmarks methodology to assess the performance of quantum error-mitigation techniques and test the methodology on superconducting hardware. To do so we use *Qermit* – an open-source python package for quantum error mitigation. Qermit provides access to an array of error mitigation schemes; with an modular software architecture which ensures that composition and re-use of methods and sub-components is straightforward.

Error-Mitigation

Input: Unitary circuit $U = U_1 \dots U_d$, observable O, pure input state ρ_0 and resource parameters $\mathcal{R} = (K$ total distinct circuits, $(n_i)_{i=1}^{K}$ shots per circuit, q device specs$)$.

Data collection: $\mathfrak{N}$ involves (i) sub-processes $\mathfrak{N}_1$, ..., $\mathfrak{N}_K$ that modify the input circuit U in a method-specific way (ii) measurement circuits $\mathfrak{M}_1(O), \dots, \mathfrak{M}_M(O)$ with classical estimator function $o_{m,i}(z)$ over measurements outcomes z.
Returns $\mathbf{D} = (D^q_{i,m}, D^c_{i,m})$, where $D^q_{i,m} := \frac{1}{n_i}\sum_{s=1}^{n_i}\sum_z o_{m,i}(z) Z_s(z)$ with Z_s i.i.d indicator random variable over measurement outcomes obtained from evaluating $\mathfrak{M}_m(O)\mathfrak{N}_i(U)(\rho_0)$ on the quantum device q. If required and available, $D^c_{i,m}$ corresponds to the exact classical simulation.

- Zero Noise Extrapolation (ZNE) [1, 2]: $\mathfrak{N}_k(U) = U(UU^\dagger)^{\frac{k-1}{2}}$
- Clifford Data Regression (CDR) [3]: $\mathfrak{N}_k(U)$ is a modified circuit s.t all except a small number N_{nc} of T gates in U (synthesized as Clifford + T) are replaced by a single-qubit Clifford gates $\{I, S, S^\dagger, Z\}$.

Functional Model: An implicit mapping $\mathfrak{F}(\mathbf{D}, \langle\hat{O}\rangle_{EM}) = 0$

Classical Data processing: Produce an output estimator $\langle\hat{O}\rangle_{EM}$ based on fitting the data to the functional model.

Benchmark Design

Volumetric benchmarking [4] of error mitigation aims to assess the overall performance of a method on a specific device (with a fixed set of resources $\mathcal{R}$) for a class of circuits with increasing depth d (as determined by the number of layers of primitive circuits) and width w (number of qubits). We use the relative mitigation error defined as

$$\epsilon(O) := \frac{|\langle\hat{O}\rangle_{EM} - \langle O\rangle|}{|\langle\hat{O}\rangle_{\text{noisy}} - \langle O\rangle|} \quad (1)$$

The methodology we use consists of the following components:

1. A class of circuits $\mathcal{C}(w, d)$ and a probability distribution or method to sample C individual circuits.
2. A global (Pauli) observable O (or set thereof).
3. Determine relative mitigation error $\epsilon_i(O)$ for each circuit $\mathcal{C}(w, d)$ labelled by $i \in \{1, \dots, C\}$.
4. Determine the median relative mitigation error over the sampled circuits $\bar{\epsilon} = \text{med}_{i=1}^{C}[\epsilon_i(O, w, d)]$.

Qermit

Qermit [5] is an open-source python module facilitating the construction, composition and execution of error-mitigation protocols.

```
pip install qermit
```

Qermit supports ZNE, CDR, PEC, SPAM error correction, frame randomisation, and several variations upon each. There are two types of methods:

MitRes : modify the distribution of shots retrieved from a backend.
MitEx : return a modified expectation value of inputted observable.

`MitRes` and `MitEx` objects are constructed as dataflow graphs, called a `TaskGraph`. Each node of a `TaskGraph` is a `MitTask` object; itself a function that computes some step or sub-process of an error-mitigation protocol. This sub-process may, for example, be the submission of a circuit to a QPU, or the modification of a circuit for the purposes of error-mitigation. Edges of the graph move data between `MitTask` objects which depend on each other. When the `run` function is called on a `MitRes` or `MitEx` object, a topological sort is applied to the graph, and the tasks are run sequentially.

This modular software architecture allows for vertices to be amended to adapt the protocol where necessary and facilitates quick prototyping of new protocols though the reuse and combination of existing sub-protocols and mitigation schemes.

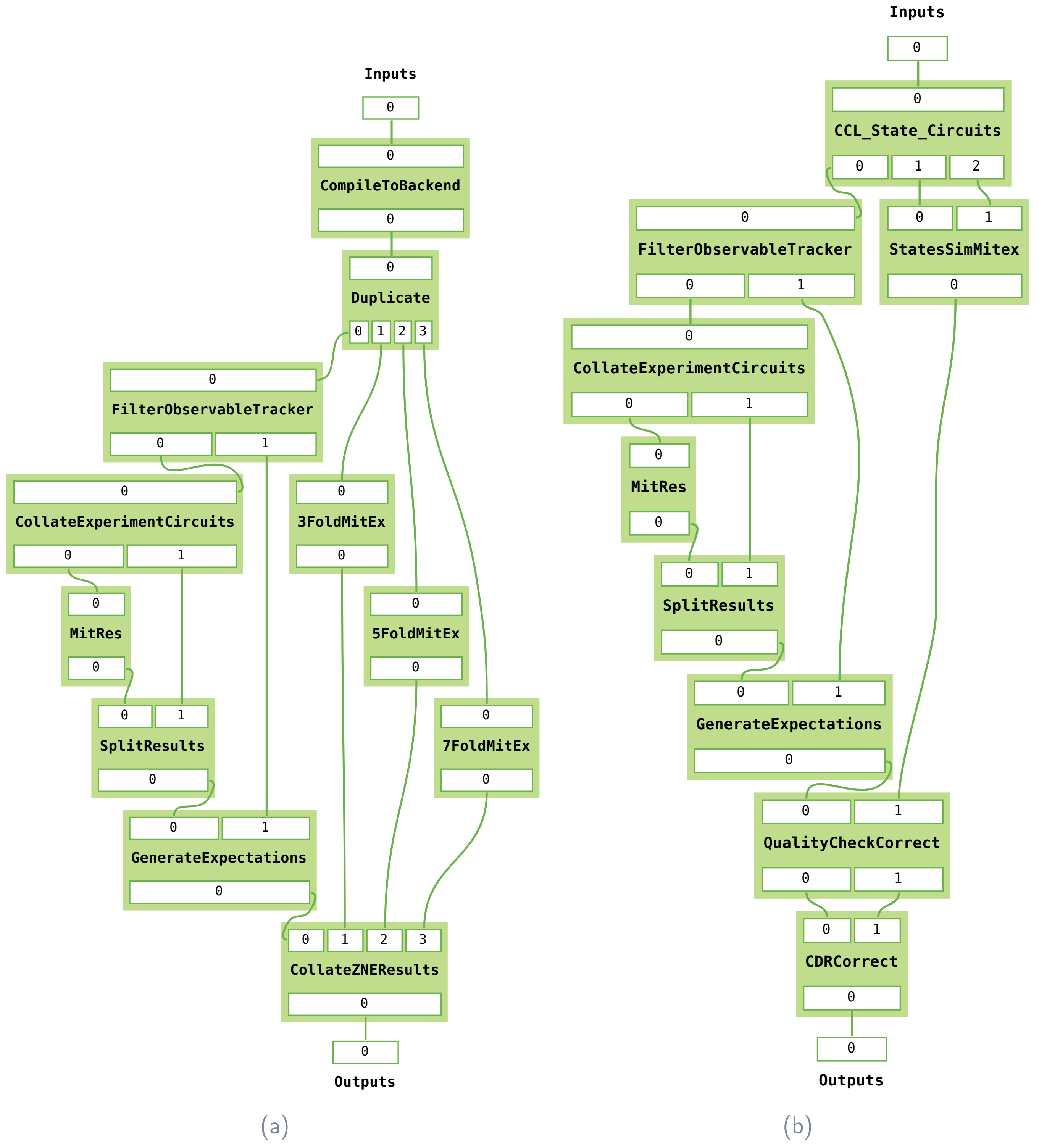
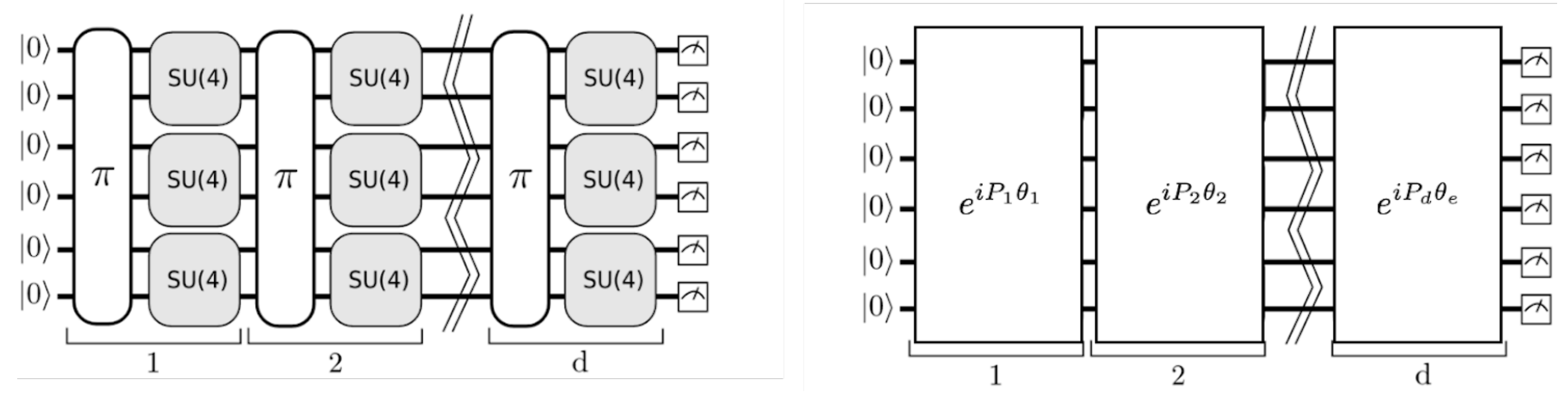


Figure 1. `TaskGraph` for (a) ZNE and (b) CDR

Results

Volumetric benchmarks [4] compare ZNE and CDR when running Pauli gadget (used in quantum chemistry simulations, seen on the left) and random (used in quantum volume experiments, seen on the right) circuits.



Shot budget per mitigated circuit: 1.6×10^5; Observable: $Z^{\otimes w}$; Circuits for fixed (w, d): 5; device: `ibmq-casablanca`.

- ZNE - exponential extrapolation via least-squares optimisation, circuit folding, noise levels = 1,3,5,7,9 with total shot budget distributed equally.
- CDR - linear regression, 20 sampled near-Clifford circuits, maximum of 10 non-Clifford gates, total shot budget distributed equally.

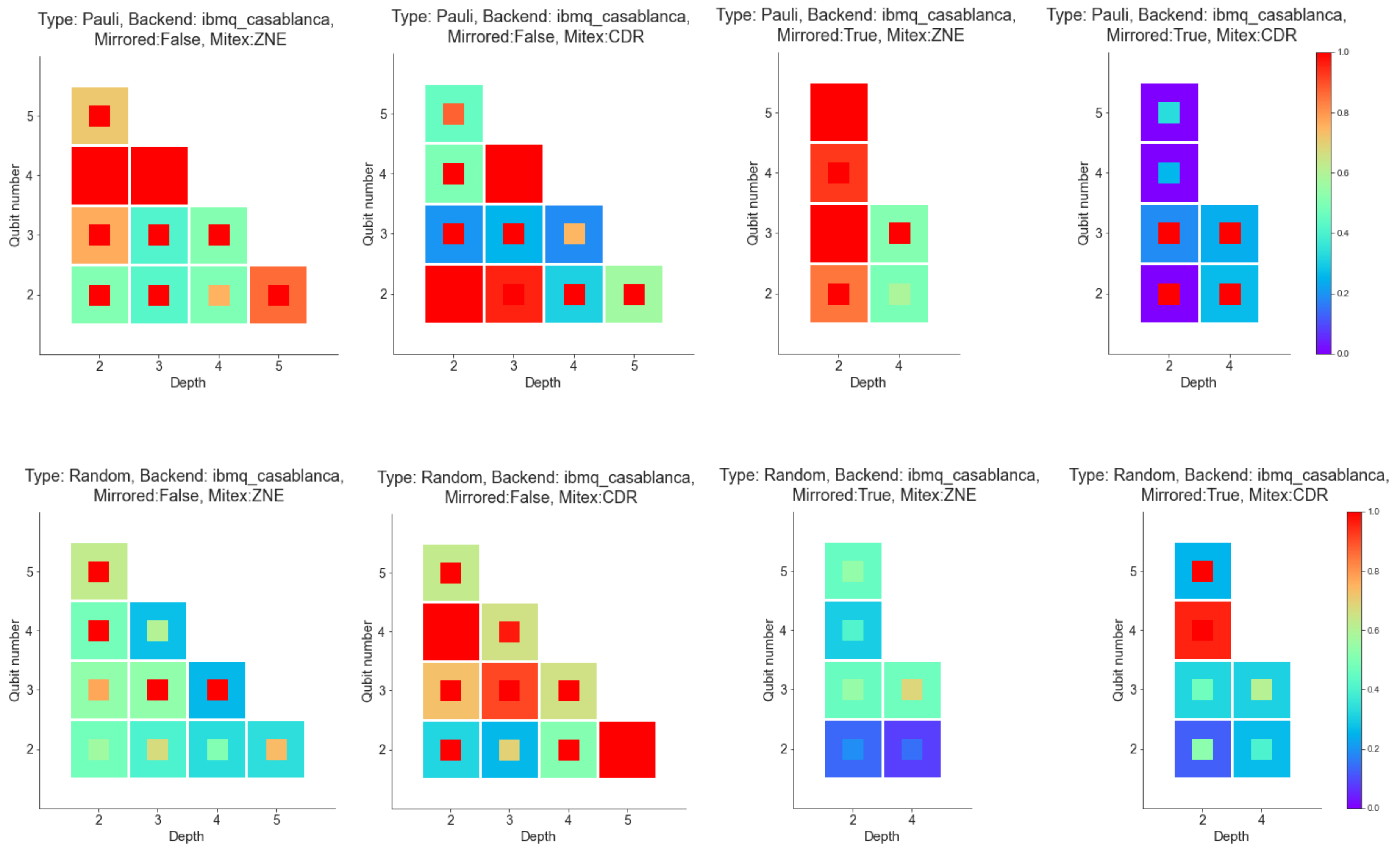


Figure 2. Median $\bar{\epsilon}$ (outer square) and worst-case (inner square) relative mitigation error over sampled circuits for fixed (w, d). $\bar{\epsilon}$ ranges between $(0, 1)$ for successful mitigation.

Please see the paper "Volumetric Benchmarking of Error Mitigation with Qermit" for further details, including comparisons between devices. Future work investigates higher shot budget regimes, and performance increase by combining with other method (such as frame randomisation).

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[1] K Temme et al. Error mitigation for short-depth quantum circuits. *Physical review letters*, 119(18):180509, 2017.
[2] T Giurgica-Tiron et al. Digital zero noise extrapolation for quantum error mitigation. *arXiv preprint arXiv:2005.10921*, 2020.
[3] P Czarnik et al. Error mitigation with Clifford quantum-circuit data. *Quantum*, 5(Nov):592, 2021.
[4] R Blume-Kohout et al. A volumetric framework for quantum computer benchmarks. *Quantum*, 4(November):362, 2020.
[5] C Cirstoiu, S Dilkes, D Mills, and S Sivarajah. Qermit. URL `https://github.com/CQCL/qermit`.

Acknowledgements: Work supported by Innovate UK ISCF Commercialising quantum technologies grant no. 10001712