Scalable Matrix Based Error Mitigation

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Introduction and Motivation

In the noisy intermediate-scale quantum (NISQ) era, quantum computers are often too noisy for meaningful computation.

- Error correction requires too many qubits with high fidelity.
- We can use classical processors to enhance the quality of the results after computation on a quantum processor ⇒ Error mitigation.

The state preparation and measurement (SPAM) protocol is a simple protocol that mitigates SPAM errors. It is used, for example, in Qiskit [1].

- Set up all possible basis states.
- Perform measurement.
- Create complete assignment matrix M (see Fig 1).
- Use least squares method to mitigate error [2] (see Equ. (1), V = measured frequencies, X = mitigated frequencies).
- <u>No gate errors considered!</u>
- Motivation for this work is to include gate errors and make the mitigation scalable.

$$\min f(x) = \sum_{i=1}^{2^N} (v_i - (MX)_i)^2 \qquad (1)$$

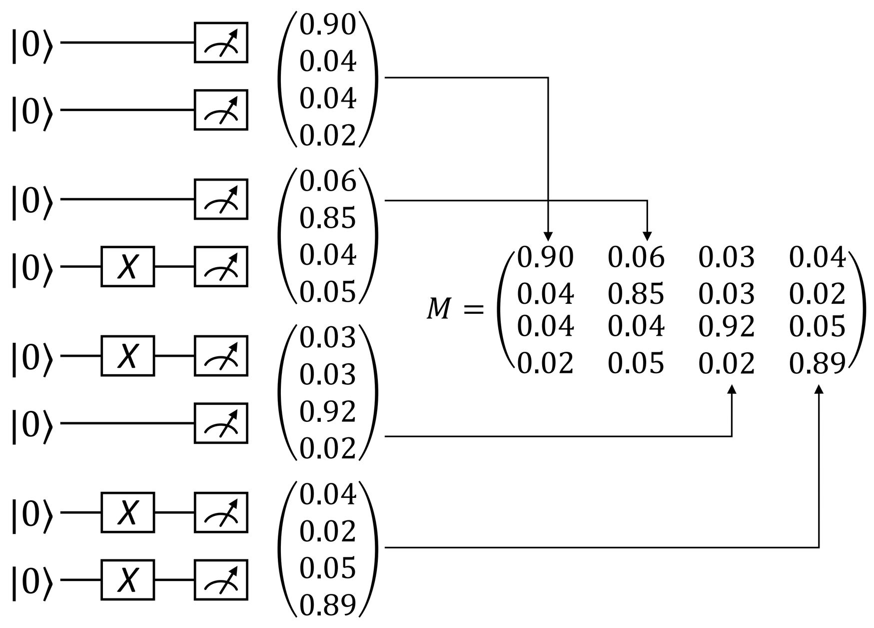

Fig 1: Creation of complete assignment matrix for SPAM protocol.

General error mitigation [2] improves SPAM protocol to consider gate errors as well.

- Split circuits in two parts.
- Invert both circuits.
- Create complete assignment matrix.
- Use least squares method to mitigate error.
- <u>Exponential number of calibration circuits (2^{N+1}) required!</u>

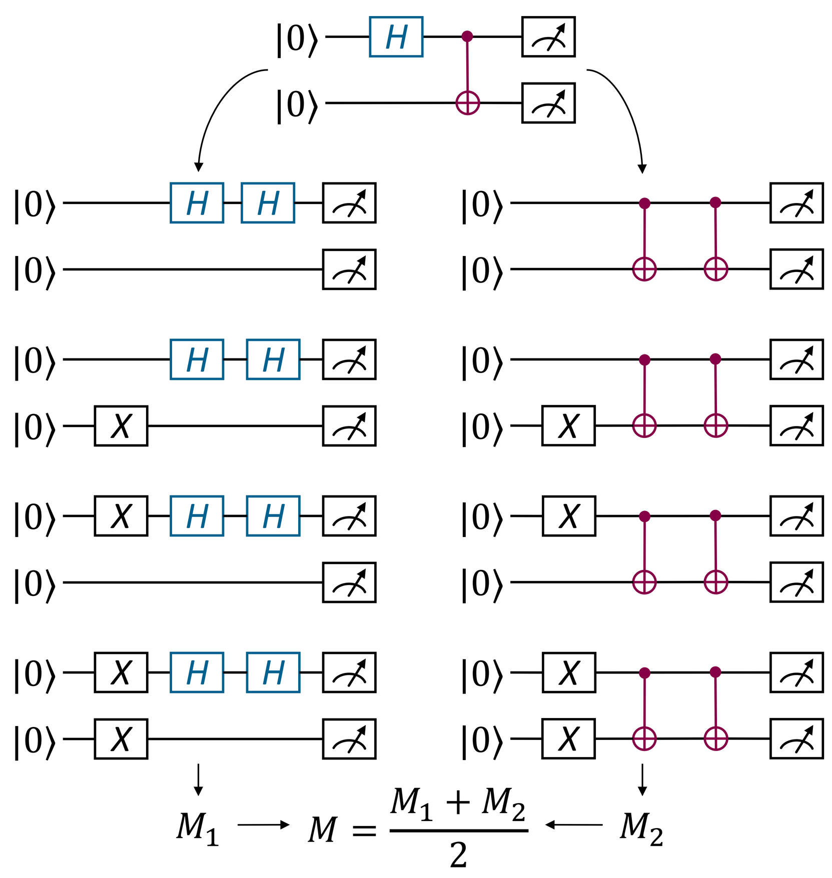

Fig 2: Creation of complete assignment matrix for the general error mitigation protocol.

Scalable Mitigation Method

How can we make the error mitigation scalable to large qubit numbers?

- Observation: Complete assignment matrix has a lot of entries close to 0 (see dark parts in Fig 3).
- Idea: Define a threshold and only consider larger entries for mitigation.
- Problem: We cannot create the full matrix.

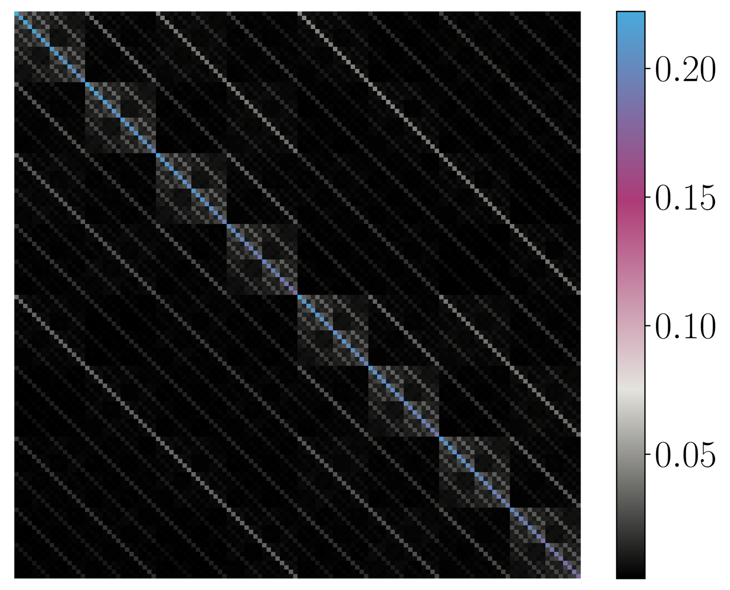

Fig 3: Average of 103 assignment matrices with 7 qubits plotted as a heat map. The columns represent the values of the measured frequencies.

- Idea: Run circuit and only consider k largest states in the output for mitigation.
- How to choose the optimal k?
- We can calculate a score that quantifies the quality of mitigation: ΔQ (see below for detail).
- There is an optimum between ΔQ and the matrix size if we use the true number of non-zero output states for mitigation (see Fig. 4).

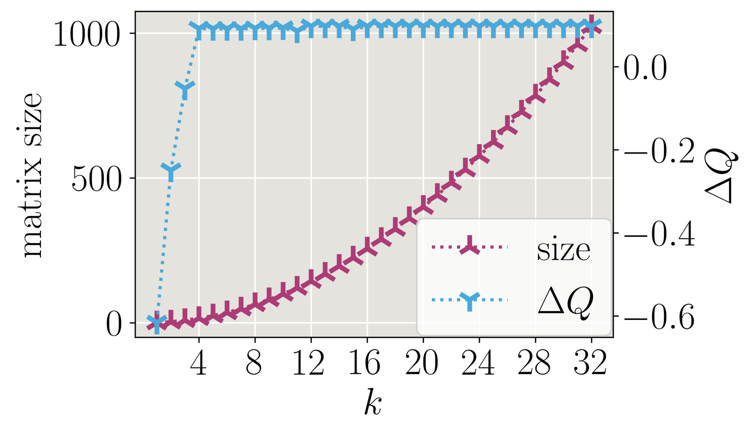

Fig 4: ΔQ and the matrix size as a function of k. We see that the mitigation quality does not improve beyond $k = 4$, which is also the number of non-zero output states for this example.

- Idea: We increase k iteratively until ΔQ becomes constant.
- Problem: Calculating ΔQ requires the simulated frequencies.
- Solution: We introduce the score ΔR which replaces ΔQ. We no longer require simulated frequencies.

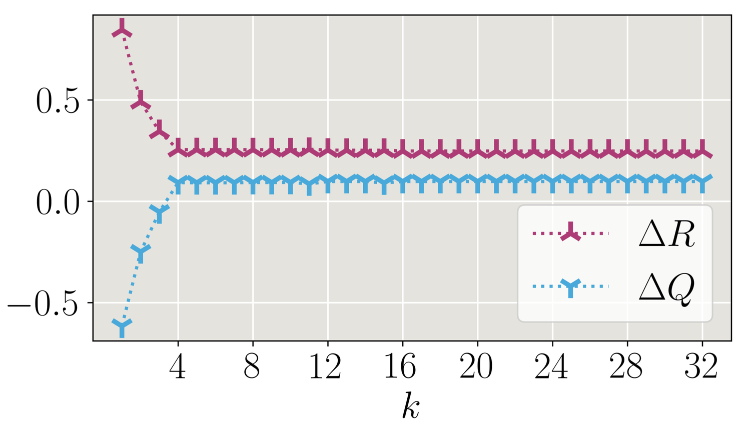

Fig 5: ΔR and ΔQ plotted as a function of k. We see that ΔR can serve as replacement for ΔQ, since the slopes of both go to zero at the same k.

$$\Delta R = \sqrt{\sum_{k=1}^{2^N} (v_k - x_k)^2} \qquad (2)$$

$$\Delta X = \sqrt{\sum_{k=1}^{2^N} (x_k - s_k)^2} \qquad (3)$$

$$\Delta V = \sqrt{\sum_{k=1}^{2^N} (v_k - s_k)^2} \qquad (4)$$

$$\Delta Q = \Delta V - \Delta X \qquad (5)$$

s: simulated frequencies
x: mitigated frequencies
v: measured frequencies

Experimental Results

We performed all tests on IBM Q superconducting devices.

- A total of 1853 random circuits were generated.
- 2-7 qubits with simulated data for comparison.
- Scaling test with 100 qubits (results not shown).

Results:

- Mitigation works comparably well using the sparse matrix (see Fig 7).
- The size of the sparse matrix is exponentially smaller (see Fig 6).

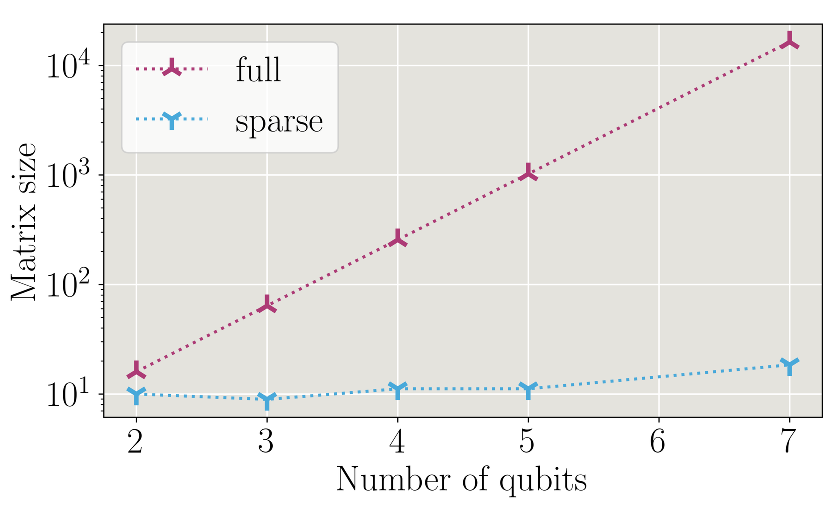

Fig 6: Average number of matrix elements for the sparse and full matrix at different circuit widths.

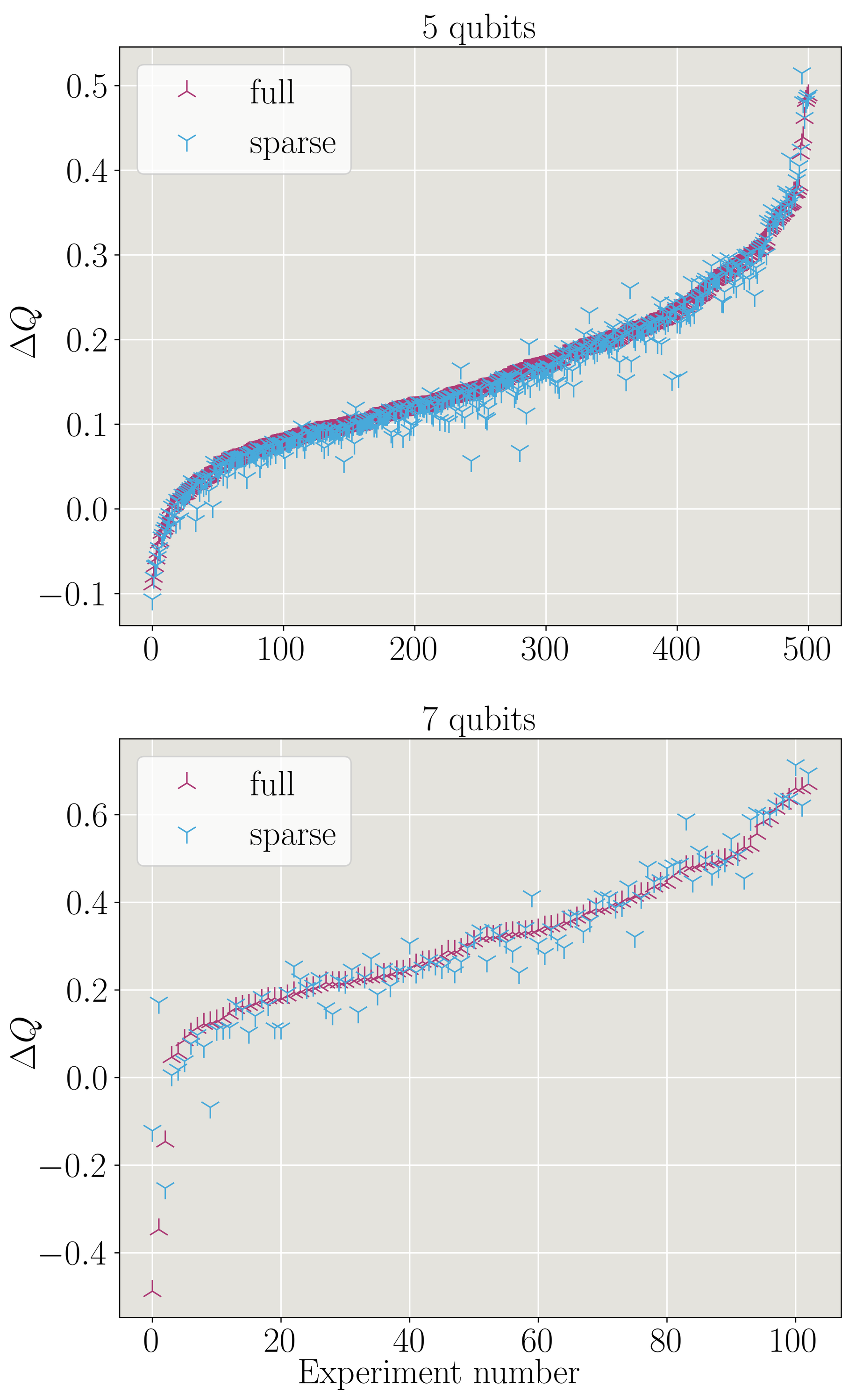

Fig 7: ΔQ for randomly created circuits with full and sparse matrices.

Conclusion

- The new mitigation protocol builds upon a general matrix based error mitigation method.
- Our tests show that the method performs comparably well while reducing the matrix size significantly.

References

1. Javadi-Abhari, A., Treinish, M., Krsulich, K., Wood, C. J., Lishman, J., Gacon, J., ... & Gambetta, J. M. (2024). Quantum computing with Qiskit. arXiv preprint arXiv:2405.08810.
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