

Benchmarking a general readout error mitigation routine on IBM and Rigetti Devices

George Polykratis

In collaboration with

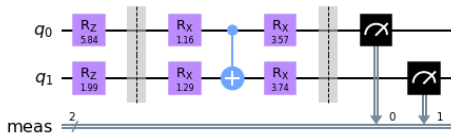
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Stefan Kühn, Tobias Hartung, Tom Weber, Xiaoyang Wang

July 29, 2021

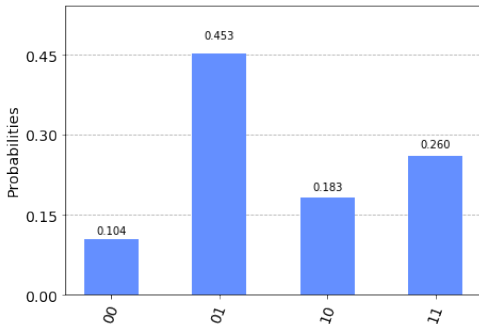


Introduction

Projective measurements on computational basis $\{|0\rangle, |1\rangle\}^{\otimes N}$

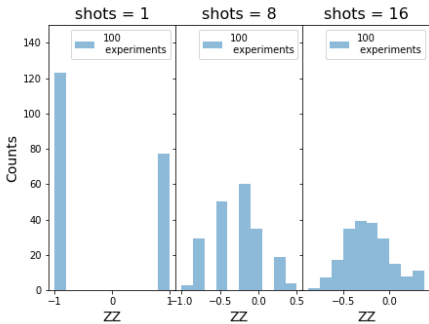
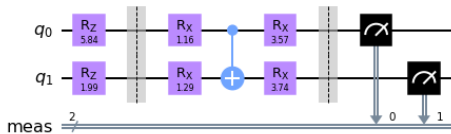


$$|\psi\rangle = a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle$$



Introduction

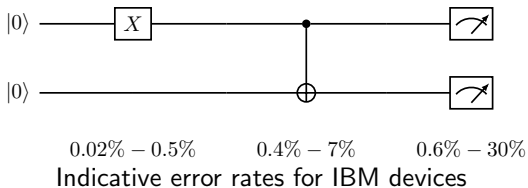
Projective measurements on computational basis $\{|0\rangle, |1\rangle\}^{\otimes N}$



Bit Flip Error

NISQ devices suffer from unavoidable sources of error:

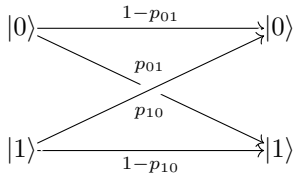
gate errors
depolarizing noise
readout error
⋮



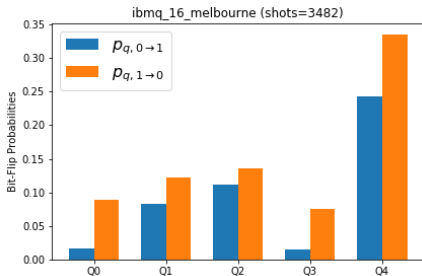
Bit Flip Error

The act of measurement comes with its own error (up to $\sim 30\%$).

For each utilized qubit:



$$p(|0\rangle \rightarrow |1\rangle) \neq p(|1\rangle \rightarrow |0\rangle)$$



Mitigation scheme

Noise free expectations of operators written in terms of noisy ones:

$$Z_q = \frac{1}{\gamma(Z_q)} \mathbb{E}(\tilde{Z}_q) - \frac{\gamma(I)}{\gamma(Z_q)} \mathbb{I},$$

$$\text{where } \gamma(O_q) = \begin{cases} 1 - p_{q,0} - p_{q,1} & \text{for } O_q = Z_q \\ p_{q,0} - p_{q,1} & \text{for } O_q = I_q. \end{cases}$$

Mitigation scheme

Noisy variance prediction:

$$\mathbb{V} \langle \psi | \tilde{Z}_q | \psi \rangle = \frac{1}{s} \mathbb{V}_{bf} \langle \psi | \tilde{Z}_q | \psi \rangle + \frac{1}{s} \mathbb{V}_{QM} \langle \psi | \tilde{Z}_q | \psi \rangle$$

Mitigation scheme

Noisy variance prediction:

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where

$$\mathbb{V}_{bf} \langle \psi | \tilde{Z}_q | \psi \rangle = a_1 \langle \psi | Z_q | \psi \rangle^2 - 2a_2 \langle \psi | Z_q | \psi \rangle + a_3$$

and

$$\mathbb{V}_{QM} \langle \psi | \tilde{Z}_q | \psi \rangle = 1 - \langle \psi | \tilde{Z}_q | \psi \rangle^2$$

arXiv:2007.03663v2

$$a_1 = (p_{q,1} + p_{q,0})(1 - p_{q,0} - p_{q,1}) + 2p_{q,0}p_{q,1},$$

$$a_2 = (1 - p_{q,0} - p_{q,1})(p_{q,1} - p_{q,0}),$$

$$a_3 = (p_{q,0} + p_{q,1} - p_{q,0}^2 - p_{q,1}^2)$$

Mitigation scheme

Noisy variance prediction:

$$\mathbb{V} \langle \psi | \tilde{Z}_q | \psi \rangle = \frac{1}{s} \mathbb{V}_{bf} \langle \psi | \tilde{Z}_q | \psi \rangle + \frac{1}{s} \mathbb{V}_{QM} \langle \psi | \tilde{Z}_q | \psi \rangle$$

Mitigated variance prediction:

$$\mathbb{V} \langle \psi | Z_q | \psi \rangle = \left(\frac{1}{\gamma(Z_q)} \right)^2 \mathbb{V} \langle \psi | \tilde{Z}_q | \psi \rangle$$

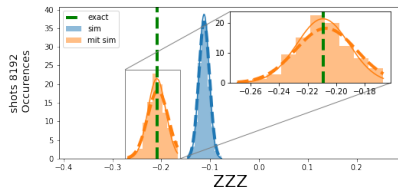
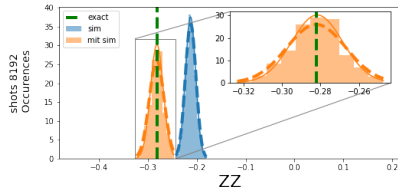
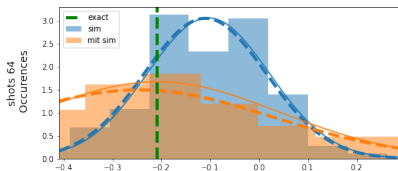
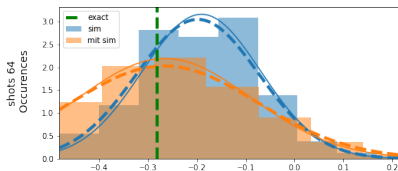
Variances simulation

Following results are for the

$$\langle \psi | Z_1 \otimes Z_0 | \psi \rangle \quad \text{and} \quad \langle \psi | Z_2 \otimes Z_1 \otimes Z_0 | \psi \rangle$$

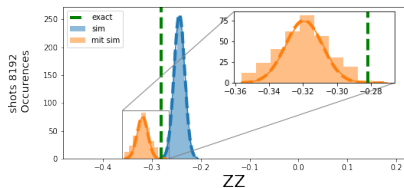
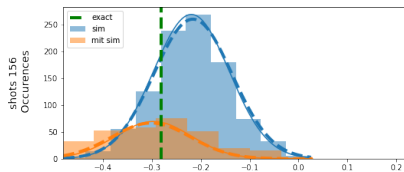
N=2 simulation

N=3 simulation

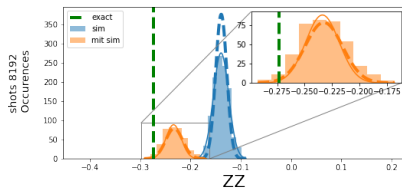
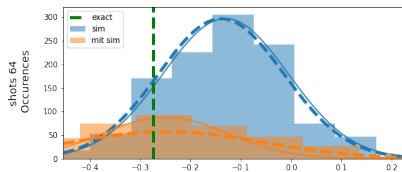


N=2 Variances on Quantum hardware

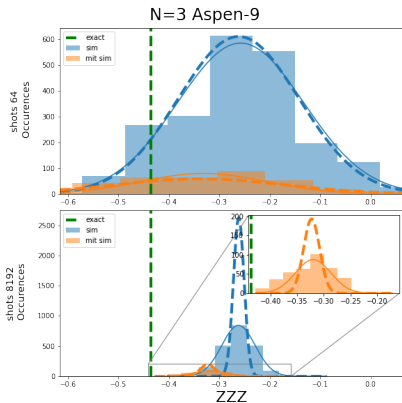
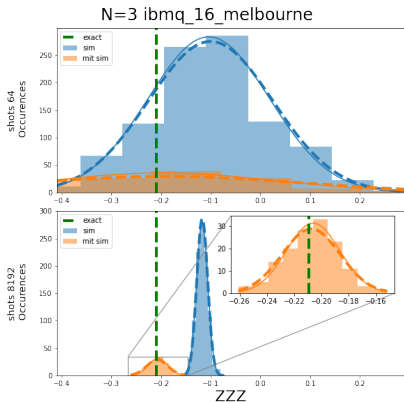
N=2 ibmq_16_melbourne



N=2 Aspen-9

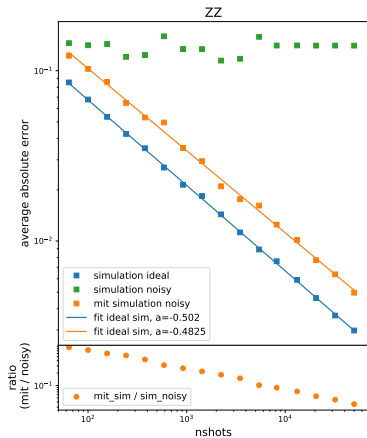


N=3 Variances on Quantum hardware

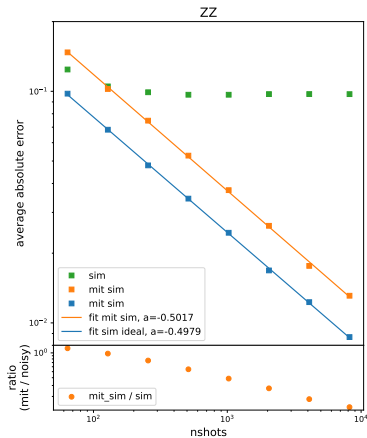


Average Absolute Error

- ▶ simulation: the mitigation of the solely readout error noise model decreases the error exponentially



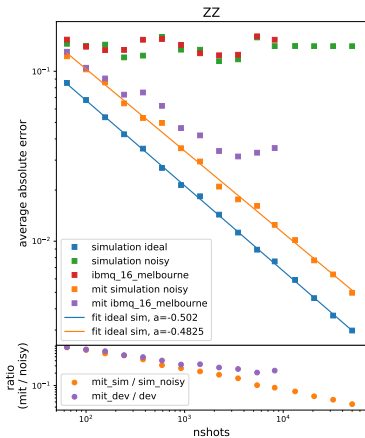
IBM (ibqm_16_melbourne)



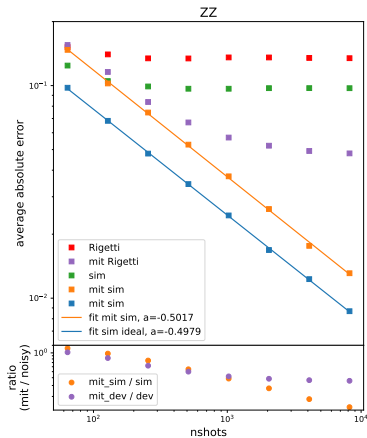
Rigetti (Aspen-9)

Average Absolute Error

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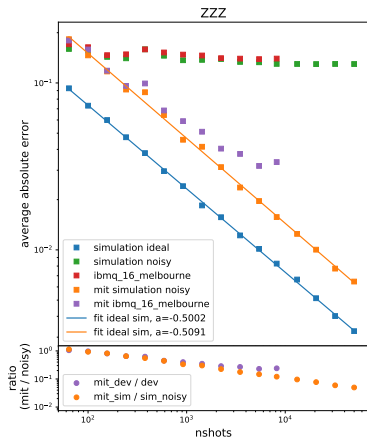


IBM (ibmq_16_melbourne)

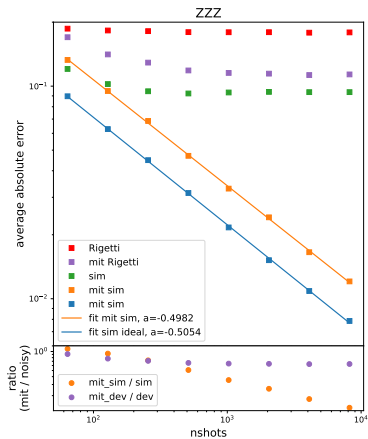


Rigetti (Aspen-9)

N=3



IBM (ibmq_16_melbourne)



Rigetti (Aspen-9)

Conclusion and road ahead

- ▶ Mitigation scheme will be important whenever readout error is a significant part of device error
- ▶ Moderate overhead cost: polynomial in the number of qubits
- ▶ This mitigation scheme can be applied on pre-processing → integrated on VQE (see Xiaoyang Wang's yesterday's talk)
- ▶ Include multi-qubit correlations with only polynomial increase to the number of calibrations needed

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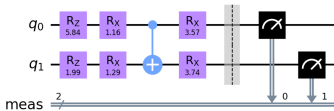
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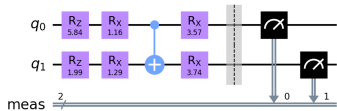
Thank you!

Appendix: Circuits used

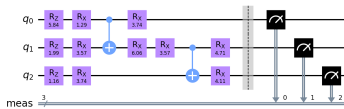
IBM:



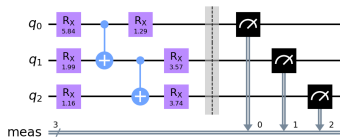
(a) N2 abs error



(b) N2 variance



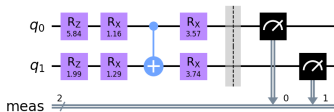
(c) N3 abs error



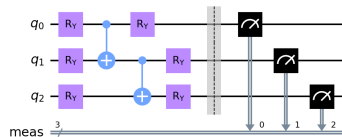
(d) N3 variance

Appendix: Circuits used

Rigetti:

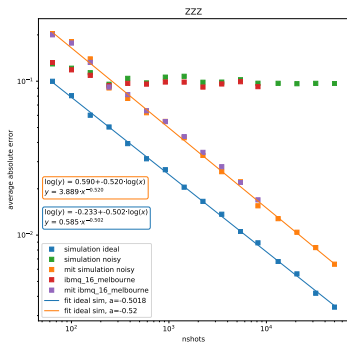
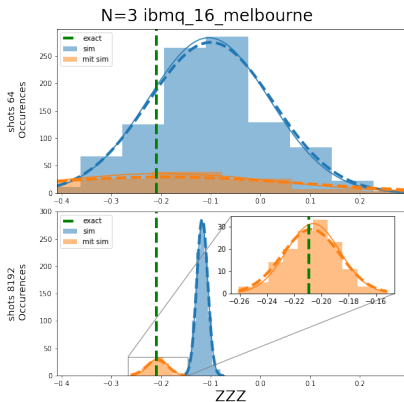


(a) N2



(b) N3

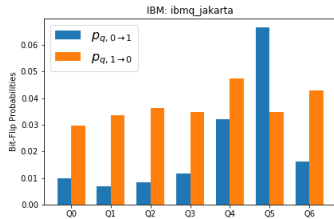
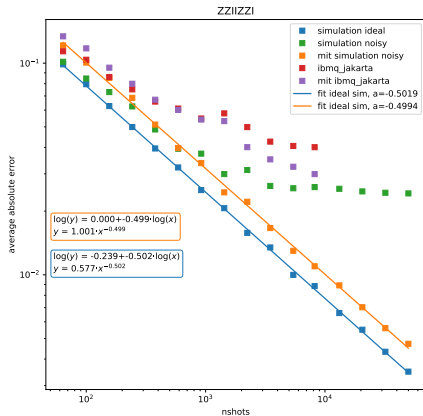
Appendix: N=3 IBM same parameters



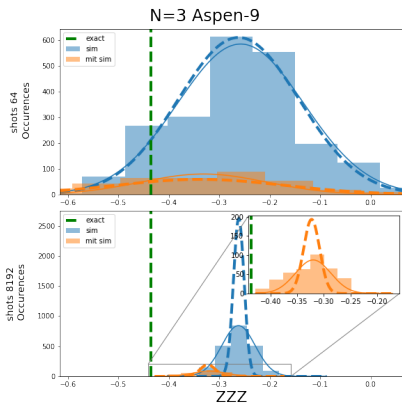
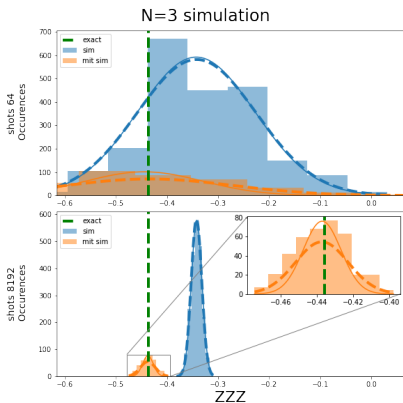
Appendix: BF Variance for $Z_1 \otimes Z_0$

$$\begin{aligned}\mathbb{V}_{bf} \langle \psi | \tilde{Z}_1 \otimes \tilde{Z}_0 | \psi \rangle &= \mathbb{V}_{bf} \langle \psi | \tilde{Z}_1 | \psi \rangle \mathbb{V}_{bf} \langle \psi | \tilde{Z}_0 | \psi \rangle + \mathbb{V}_{bf} \langle \psi | \tilde{Z}_1 | \psi \rangle \langle \psi | \tilde{Z}_0 | \psi \rangle^2 + \langle \psi | \tilde{Z}_1 | \psi \rangle^2 \mathbb{V}_{bf} \langle \psi | \tilde{Z}_0 | \psi \rangle \\ &= \left(a_{1,1} \langle \psi | Z_1 | \psi \rangle^2 - 2a_{1,2} \langle \psi | Z_1 | \psi \rangle + a_{1,3} \right) \left(a_{0,1} \langle \psi | Z_0 | \psi \rangle^2 - 2a_{0,2} \langle \psi | Z_0 | \psi \rangle + a_{0,3} \right) \\ &\quad + \left(a_{1,1} \langle \psi | Z_1 | \psi \rangle^2 - 2a_{1,2} \langle \psi | Z_1 | \psi \rangle + a_{1,3} \right) \langle \psi | \tilde{Z}_0 | \psi \rangle^2 \\ &\quad + \langle \psi | \tilde{Z}_1 | \psi \rangle^2 \left(a_{0,1} \langle \psi | Z_0 | \psi \rangle^2 - 2a_{0,2} \langle \psi | Z_0 | \psi \rangle + a_{0,3} \right)\end{aligned}$$

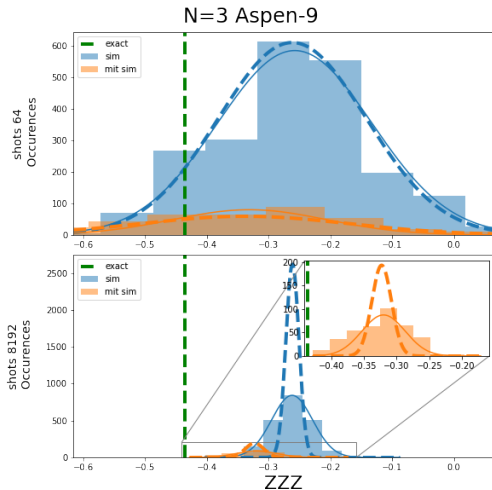
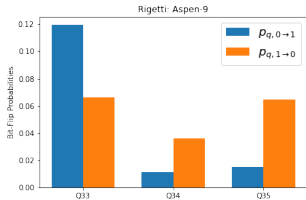
Appendix: N=7 results on ibmq_jakarta



Appendix: Rigetti Variance N=3



Appendix: Rigetti Variance N=3



Appendix: Spontaneous decay $|1\rangle \rightarrow |0\rangle$

