Research on methods of simulation of Twirled Readout Error eXtinction

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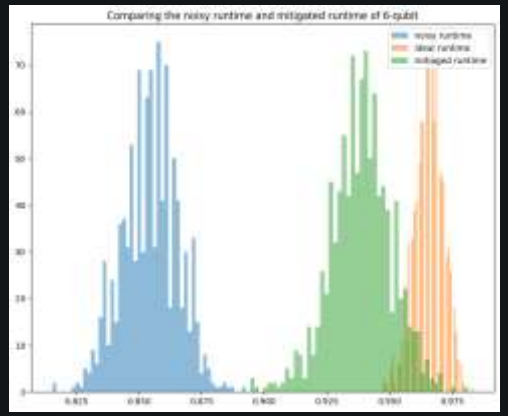
Qiskit

Project Goal

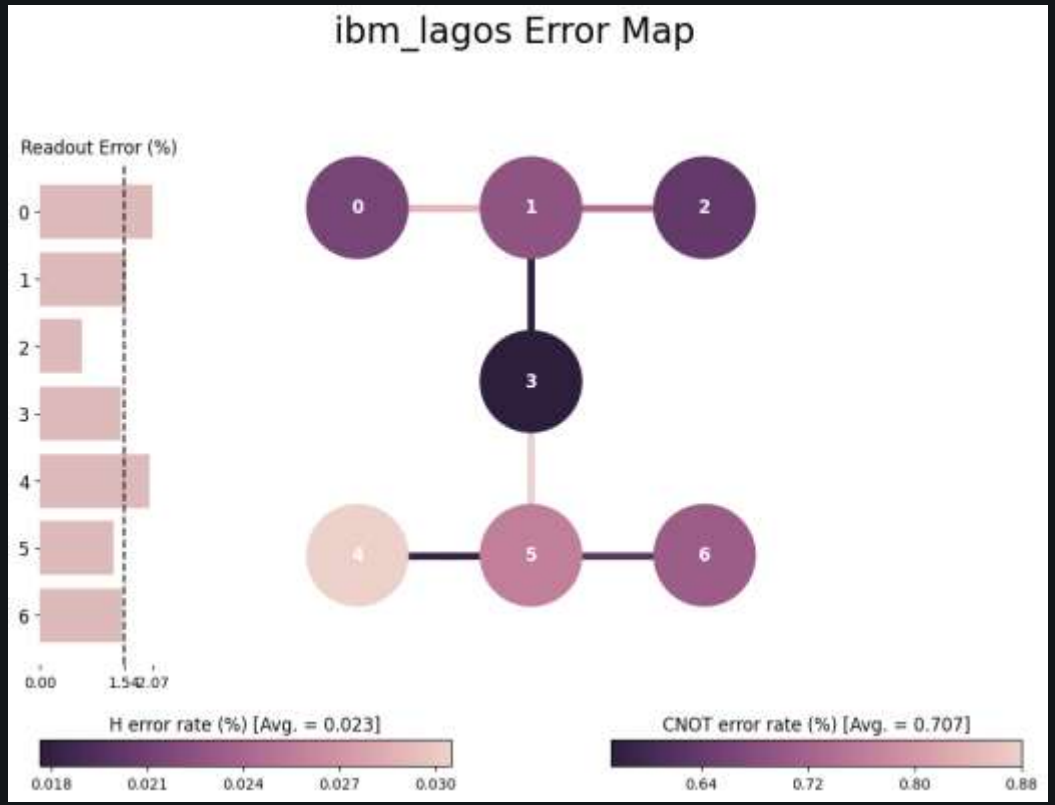
- TREX:
  - Focused on reducing noise of quantum measurement
  - The TREX technique can be applied to general noise models, not just specific forms of noise.
- **Goal: Looks for methods to simulate this technique at high speed without running calibration directly.**

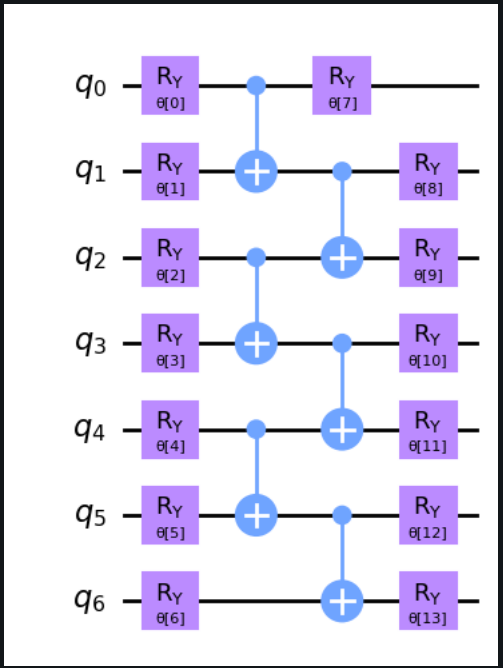


T-Rex

- This feature is enabled by setting `resilience_level=1` in `Options` with Estimator
- Implementation which involves "twirling" of gates
- View noise as a set of **extra probabilistic gates** on top of our perfect circuit implementation
  - Conjugate this noisy gate set with a gate randomly chosen from a set of gates
- Inserts pairs of Pauli gates (I, X, Y, Z) **before** and **after** entangling gates such that the overall unitary is the same
- Turning **coherent errors** into **stochastic errors**
  - **Stochastic errors can be eliminated by sufficient averaging**

Backend: “ibm_lagos”, Circuit





Configuration of Backend

```
Qubit 0 has a
  - T1 time of 97.16982851538098 microseconds
  - T2 time of 48.661135924521474 microseconds
  - U2 gate error of 0.00021401099001962178
  - U2 gate duration of 35.55555555555556 nanoseconds
  - resonant frequency of 5.235351201097817 GHz
  - prob_meas1_prep0 of 0.027800000000000047
  - prob_meas0_prep1 of 0.0136
Qubit 1 has a
  - T1 time of 133.8643297199817 microseconds
  - T2 time of 82.2345548408655 microseconds
  - U2 gate error of 0.00022611394746802253
  - U2 gate duration of 35.55555555555556 nanoseconds
  - resonant frequency of 5.099653677777586 GHz
  - prob_meas1_prep0 of 0.016
  - prob_meas0_prep1 of 0.015800000000000036
Qubit 2 has a
  - T1 time of 121.02932665457163 microseconds
  - T2 time of 182.2438367728364 microseconds
  - U2 gate error of 0.00020394683292009286
  - U2 gate duration of 35.55555555555556 nanoseconds
  - resonant frequency of 5.18829871145183 GHz
  - prob_meas1_prep0 of 0.006399999999999961
  - prob_meas0_prep1 of 0.0088
Qubit 3 has a
...
  (0, 0)        0.9836
```

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Qubit 3 has a
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```

```
A_matrices_sparse[0]
  (0, 0)        0.9864
  (0, 1)        0.027800000000000047
  (1, 0)        0.0136
  (1, 1)        0.9722
A_matrices_sparse[1]
  (0, 0)        0.9842
  (0, 1)        0.016
  (1, 0)        0.015800000000000036
  (1, 1)        0.984
A_matrices_sparse[2]
  (0, 0)        0.9912
  (0, 1)        0.006399999999999961
  (1, 0)        0.0088
  (1, 1)        0.9936
A_matrices_sparse[3]
  (0, 0)        0.9834
  (0, 1)        0.01319999999999999
  (1, 0)        0.0166
  (1, 1)        0.9868
A_matrices_sparse[4]
  (0, 0)        0.9754
  (0, 1)        0.0154
  (1, 0)        0.024599999999999955
  (1, 1)        0.9846
...
```

A* Matrix

$$X_s := \sum_a |a+s\rangle\langle a| = \sum_a |a\rangle\langle a+s| = X_s^\dagger,$$

$$A^\star := \frac{1}{2^n}\sum_s X_s A X_s^\dagger = \frac{1}{2^n}\sum_s \sum_{a,b} A_{a,b} X_s |a\rangle\langle b| X_s^\dagger$$

$$= \frac{1}{2^n}\sum_s \sum_{a,b} A_{a,b} |a+s\rangle\langle b+s|,$$

van den Berg, E., Minev, Z. K. & Temme, K. Model-free readout-error mitigation for quantum expectation values. *Physical Review A* **105,** (2022).

A star matrix

7 Qubits:

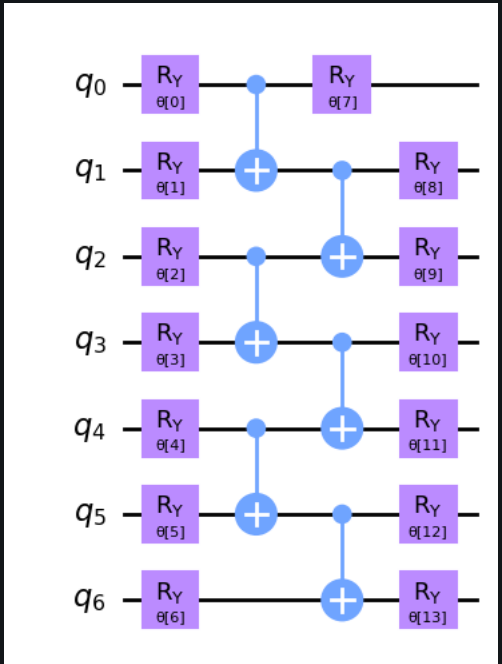
128 X 128 Comprssed Sparse Matrix

```
  (0, 0)        (0.8971837217205242+0j)
  (0, 1)        (0.013755177376362985+0j)
  (0, 2)        (0.012185548217165037+0j)
  (0, 3)        (0.00018682280239536178+0j)
  (0, 4)        (0.01830987187184741+0j)
  (0, 5)        (0.00028071790564006065+0j)
  (0, 6)        (0.0002486846574931636+0j)
  (0, 7)        (3.8127102529665636e-06+0j)
  (0, 8)        (0.013570233939331856+0j)
  (0, 9)        (0.00020805211948818 24+0j)
  (0, 10)       (0.00018431090085855128+0j)
  (0, 11)       (2.825763633835031e-06+0j)
  (0, 12)       (0.00027694354978228 24+0j)
  (0, 13)       (4.245961622207797e-06+0j)
  (0, 14)       (3.7614469562969615e-06+0j)
  (0, 15)       (5.766864558846994e-08+0j)
  (0, 16)       (0.006870814475086624+0j)
  (0, 17)       (0.00010533993154006292+0j)
  (0, 18)       (9.331939384366583e-05+0j)
  (0, 19)       (1.430726822052343e-06+0j)
  (0, 20)       (0.00014022070357319627+0j)
  (0, 21)       (2.14979452122577e-06+0j)
  (0, 22)       (1.9044774253809345e-06+0j)
  (0, 23)       (2.9198506572496765e-08+0j)
  (0, 24)       (0.00010392359727823645+0j)
...
  (127, 124)    (0.00018682280239536172+0j)
  (127, 125)    (0.012185548217165033+0j)
  (127, 126)    (0.013755177376362985+0j)
  (127, 127)    (0.8971837217205239+0j)
```

Add ReadoutError for NoiseModel

```
NoiseModel:
  Basis gates: ['cx', 'id', 'rz', 'sx']
  Instructions with noise: ['measure']
  Qubits with noise: [0, 1, 2, 3, 4, 5, 6]
  Specific qubit errors: [('measure', (0, 1, 2, 3, 4, 5, 6))]
```

Test the Circuit



$\theta = 0.2$

```
# Simulate the circuits with noise
shots = 1024

Z = SparsePauliOp.from_list([("Z",1)])
ZZZZZZZ = Z^Z^Z^Z^Z^Z^Z
```

Compare the Result

```
A star (AerEstimator):  0.740234375
Ideal (AerEstimator):  0.77734375
Noisy (AerEstimator):  0.63671875
```

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A star (AerEstimator):  0.75390625
Ideal (AerEstimator):  0.765625
Noisy (AerEstimator):  0.60546875
```

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Ideal (AerEstimator):  0.765625
Noisy (AerEstimator):  0.60546875
```

```
A star (AerEstimator):  0.75
Ideal (AerEstimator):  0.765625
Noisy (AerEstimator):  0.615234375
```

Compare the Result

```
A star (AerEstimator):  0.740234375
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```

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A star (AerEstimator):  0.75390625
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```
A star (AerEstimator):  0.75
Ideal (AerEstimator):  0.765625
Noisy (AerEstimator):  0.615234375
```

```
A star (AerEstimator):  0.767578125
Ideal (AerEstimator):  0.771484375
Noisy (AerEstimator):  0.615234375
```

Compare the Result

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A star (AerEstimator):  0.740234375
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```
A star (AerEstimator):  0.75
Ideal (AerEstimator):  0.765625
Noisy (AerEstimator):  0.615234375
```

```
A star (AerEstimator):  0.767578125
Ideal (AerEstimator):  0.771484375
Noisy (AerEstimator):  0.615234375
```

```
TREX result (Runtime):  0.7605636856368565
Noisy Result (Runtime):  0.61830078125
```

```
TREX result (Runtime):  0.7548792328438718
Noisy Result (Runtime):  0.618322265625
```

Contribution

- **Successful** implement Fast TREX Readout error mitigation in AerEstimator

- Todo:
  - Study and Compare the real efficiency of this method.
  - Make it into the feature for AerEstimaor and send PR.
  - Possibily to write it as a paper.