Analyzing the Effect of Mid-Circuit Measurement (MCM) on Spectator Qubits

Unless noted, all images were created by the author

Introduction

- Quantum Computers can solve complex problems much faster than classical computers, but are very prone to error
- Quantum error correction (QEC) is needed, and the quantum gate Mid-Circuit Measurement (MCM) is a common tool in many QEC protocols
- However, stray effects from the MCM pulse may cause error in the nearby, ultrasensitive spectator qubits

Research Question/Hypothesis

Research Question: What effect does MCM have on spectator qubit error, and how does qubit proximity affect this error?

Hypothesis: MCM-induced spectator qubit error will be significant and dependent on qubit proximity

Interleaved Randomized Benchmarking (IRB)

- IRB is a technique to analyze the fidelity of quantum gates

$$C_1, G, C_2, G, C_3, G, \ldots, C_{N-1}, G, C^{\dagger}_{inverse}$$

Figure 1: General form for IRB. Each C_n is a random Clifford gate, G is the MCM gate, $C^{\dagger}_{inverse}$ is the inverse of all prior Clifford gates, and N is the length of the IRB sequence

- All the Clifford gates were implemented on the spectator qubit, and all the MCM gates were implemented on the measured qubit
- The spectator qubit should return to its starting state of 0, so any 1 measurements can be considered an error

Benchmarking Circuit Construction

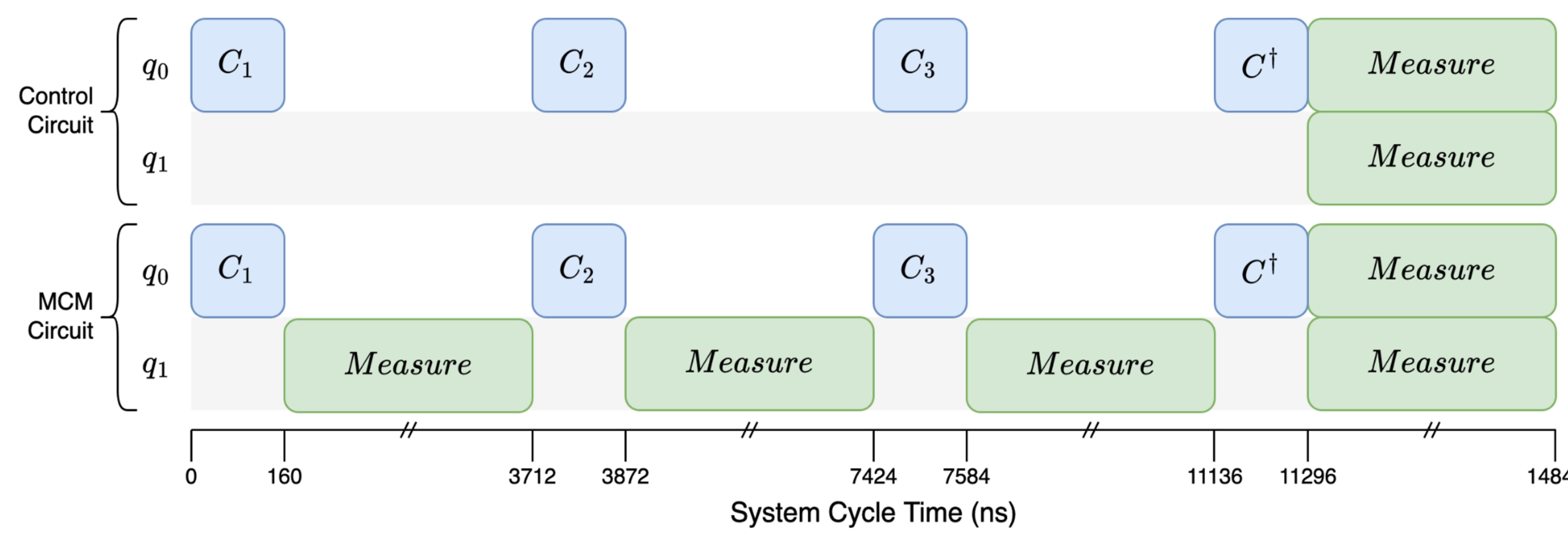

Figure 2: Example benchmarking circuits of length 4

- The MCM circuit gathers spectator qubit error when MCM is applied to a nearby qubit (Fig. 2)
- The control circuit establishes a baseline error rate to compare to the MCM circuit (Fig. 2)
- Any difference between the error rates of the MCM and control circuit can be attributed to the MCM gate

Execution Protocol

- The control and MCM circuits were sequentially generated from a length of 1 to 70
- All circuits were executed 3000 times each on all IBM 7 qubit quantum computers
- The 0/1, 0/6, and 4/6 measured-spectator qubit pairs were tested to observe the effect of qubit proximity (Fig. 3)

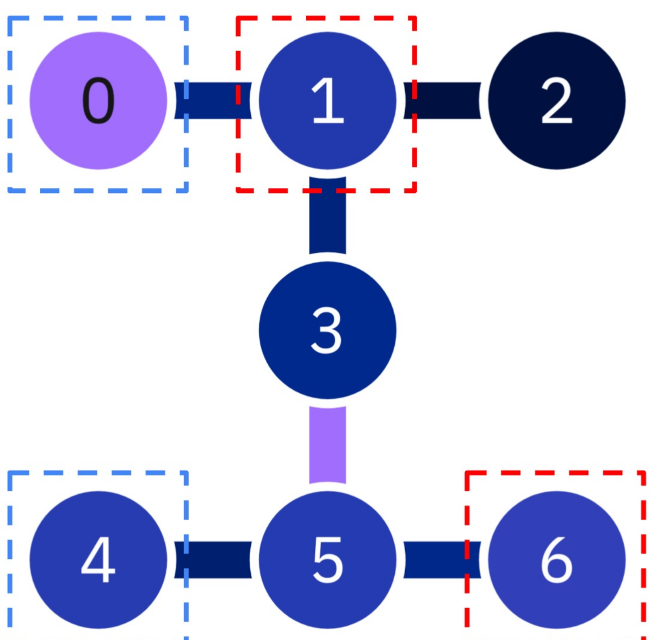

Figure 3: IBM qubit arrangement; Blue boxes are measured qubits, red boxes are spectators. Credit: IBM Quantum

Results

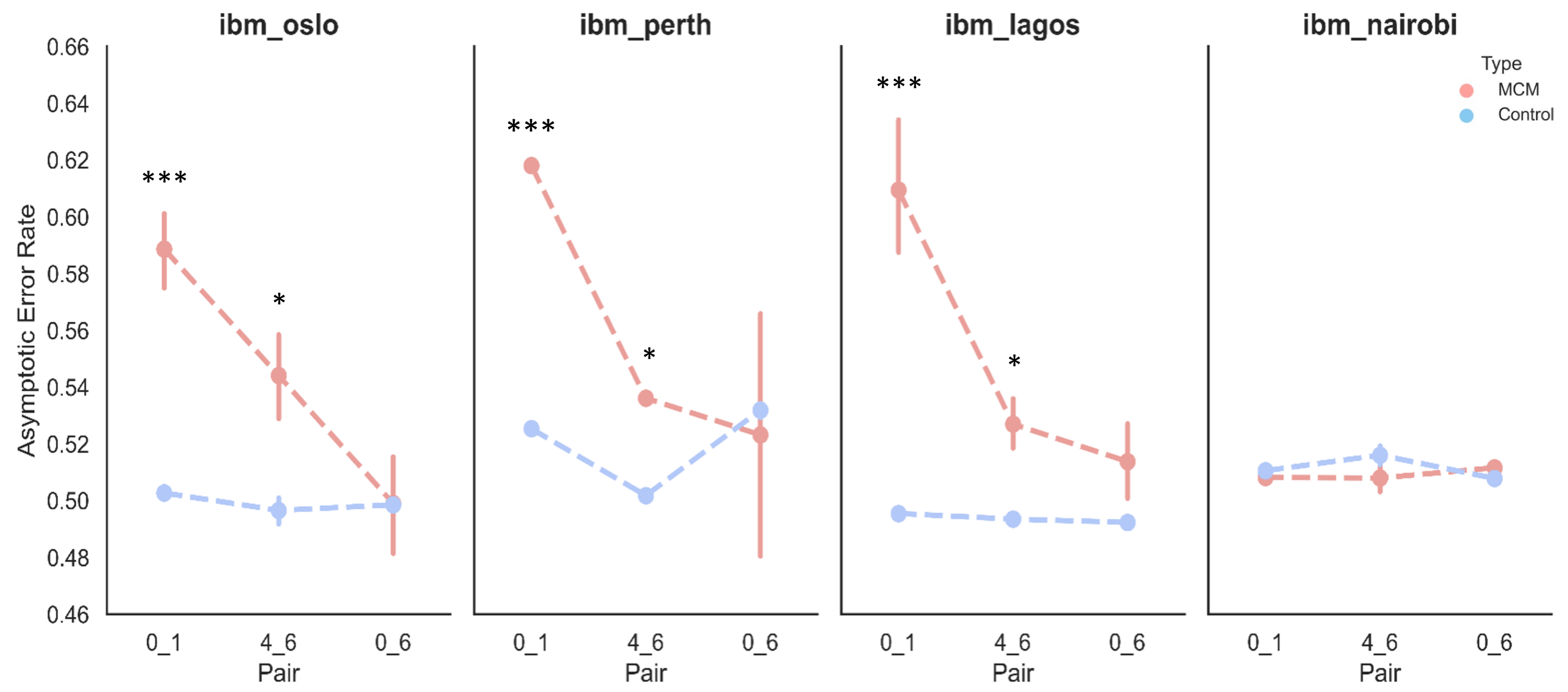

Figure 4: Asymptotic error rates of 0/1, 4/6, and 0/6 qubit pairs in various quantum computers. *** represents p < 0.005, ** represents p < 0.01, and * represents p < 0.05. All p-values were determined by t-tests.

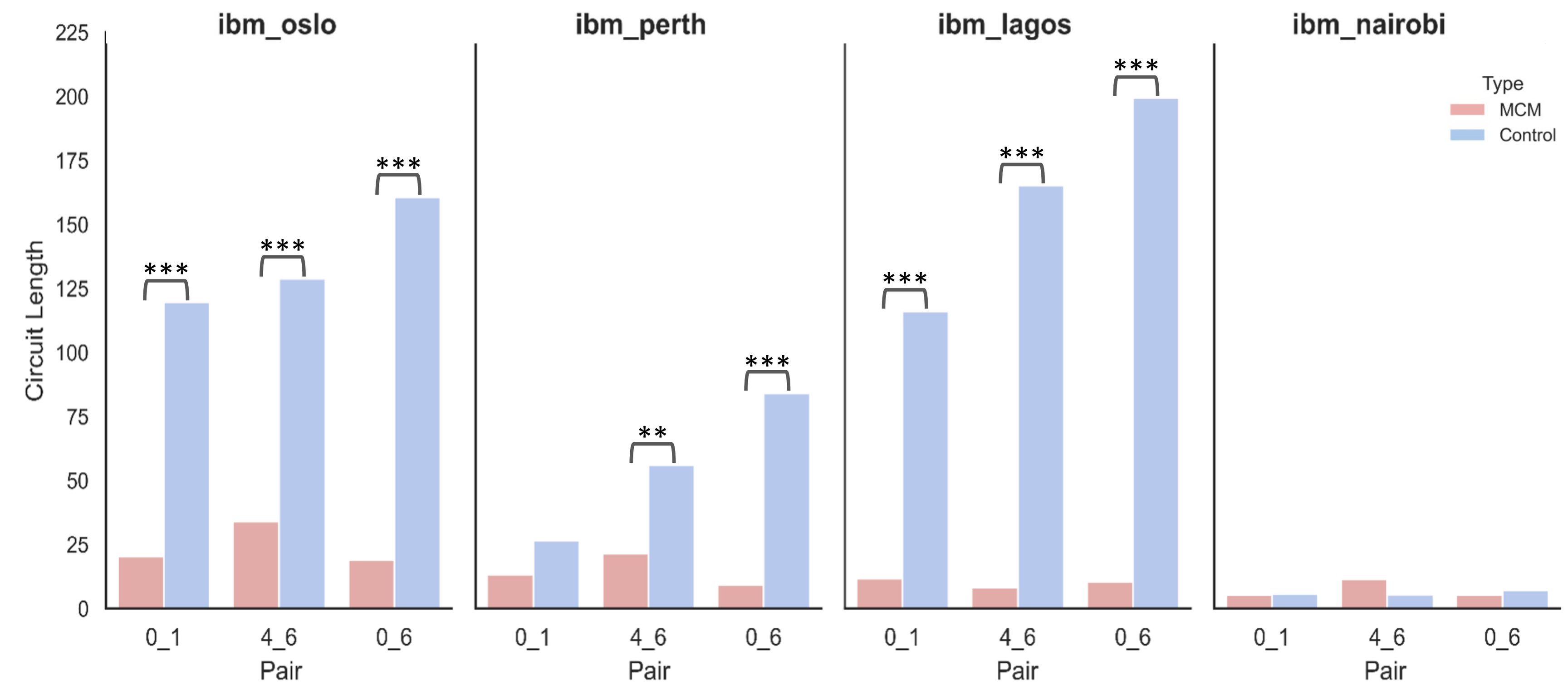

Figure 5: Circuit length where asymptotic error rate was reached in the 0/1, 4/6, and 0/6 qubit pairs. *** represents p < 0.005, ** represents p < 0.01, and * represents p < 0.05. All p-values were determined by t-tests.

- 3 quantum computers exhibited altered asymptotes that normalized toward 0.5 as qubit proximity decreased, which suggests that MCM-induced spectator qubit error is non-random and may be reduced as spectator-measured qubit distance increases (Fig. 4)
- 3 quantum computers had MCM circuits that needed a significantly smaller circuit length to reach the asymptotic error rate, showing that the inclusion of MCM causes spectator qubits to reach their "max" error rate much faster (Fig. 5)
- While the other 3 QCs all exhibited significant MCM-induced error, ibm_nairobi showed no such error, suggesting that this error highly depends on the quantum computer used (Fig. 4, 5)
  - This could imply that MCM error is dependent on quantum computer-specific factors (e.g. qubit frequency, T1/T2 time)
- When comparing these results to IBM's Aer quantum simulator, it was found that the simulator didn't account for MCM error

Conclusion

- MCM-induced spectator qubit error can be significant with high qubit proximity
- The effect of MCM on spectator qubits likely lessens as spectator-measured qubit distance increases
- Quantum algorithms may be able to take advantage of the effect of qubit proximity to reduce MCM error
- MCM error is not uniform across all quantum computers
- MCM error is likely non-random and correlated,
- When present, MCM error reduces the maximum coherent length of a circuit
- IBM Quantum simulators don't account for MCM error