Dancing the Quantum Waltz: Compiling Three-Qubit Gates on Four-Level Architectures

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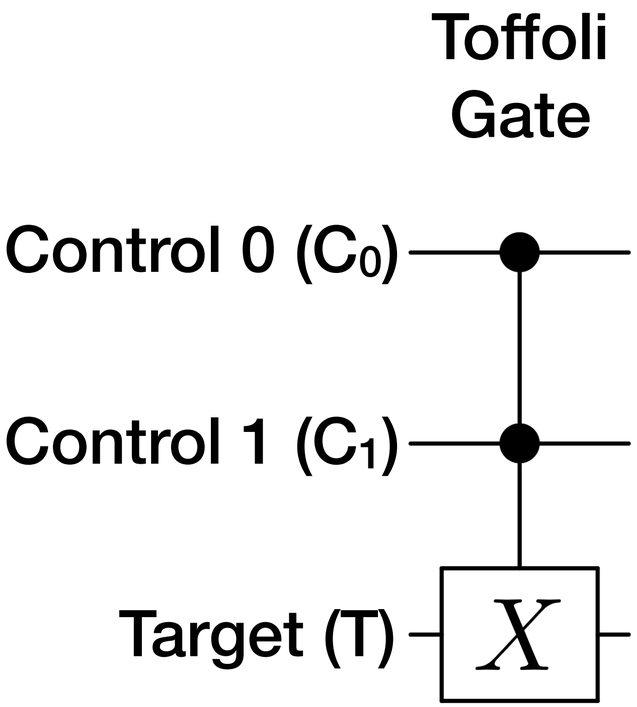
Three Qubit Gates Are Common



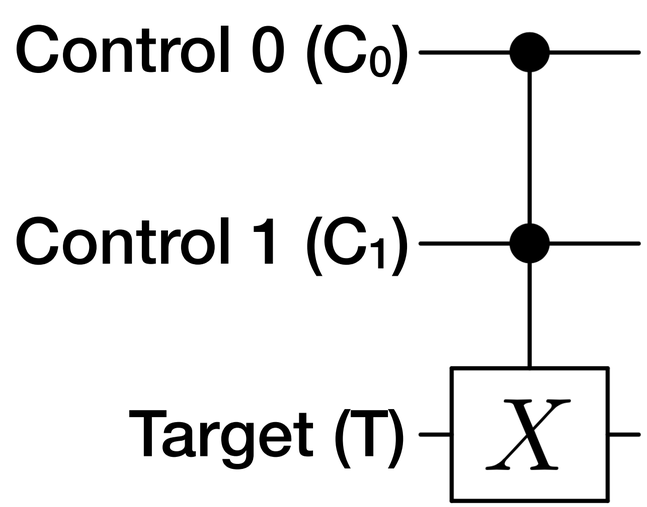
But, Three Qubit Gates Are Hard

Toffoli Gate

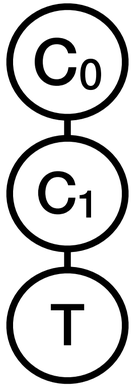
Control 0 (C_0)

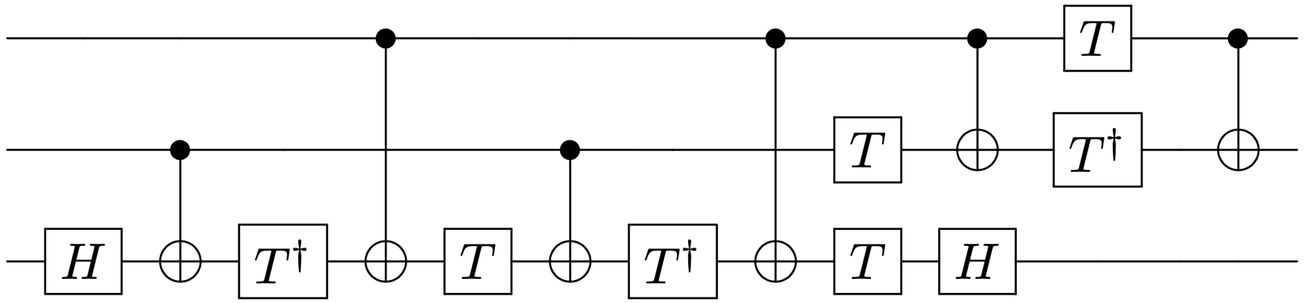
Control 1 (C_1)

Target (T)



Currently





Decomposed Toffoli Gate

14-16 Gates, 2105 ns

Four Levels Enable Fast Native Gates

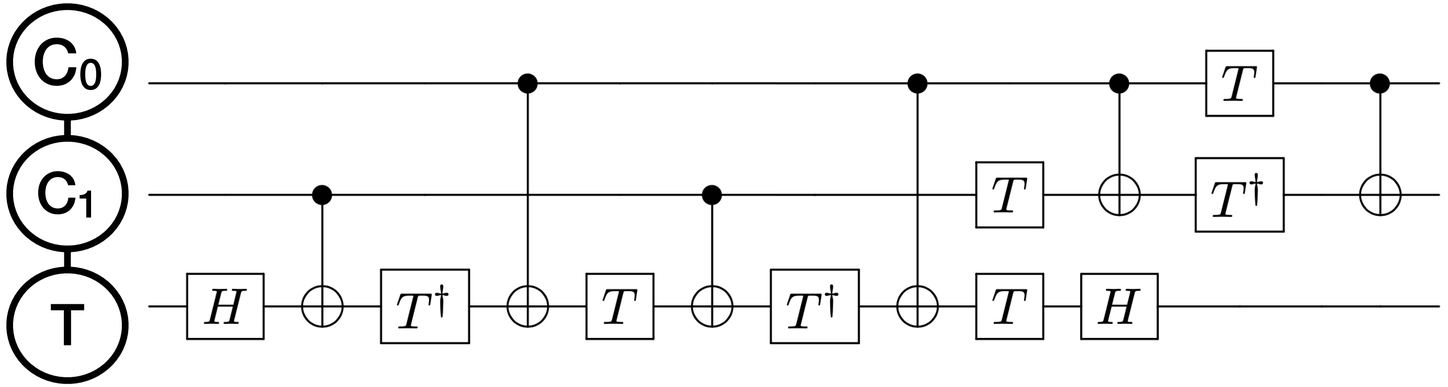
Toffoli Gate

Control 0 (C_0)

Control 1 (C_1)

Target (T) — X

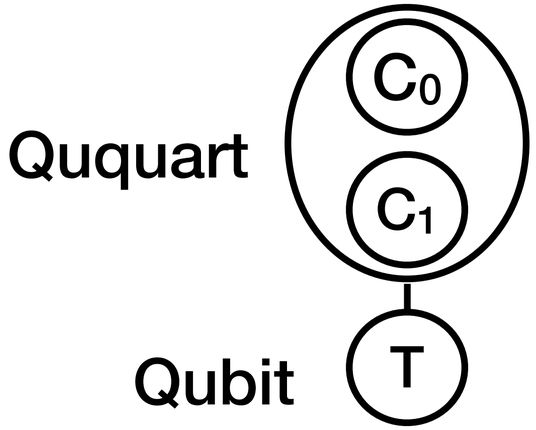
Currently



Decomposed Toffoli Gate

14-16 Gates, 2105 ns

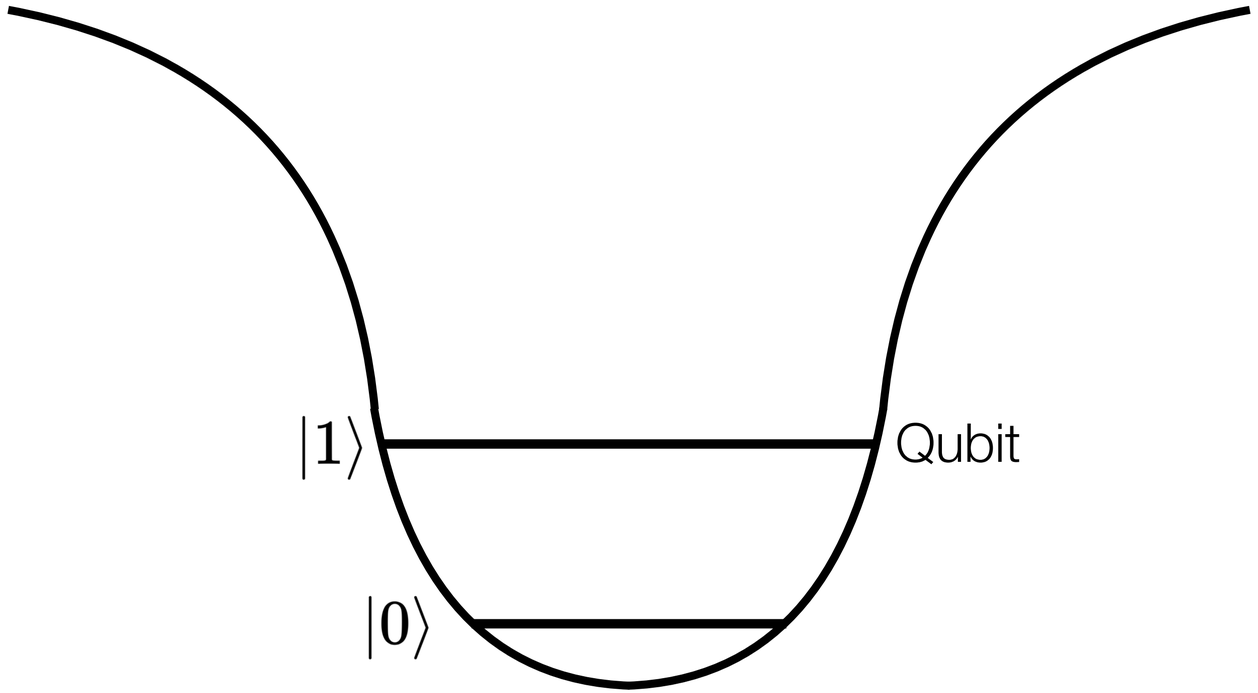
The Quantum Waltz



Ququart-Qubit Toffoli Gate

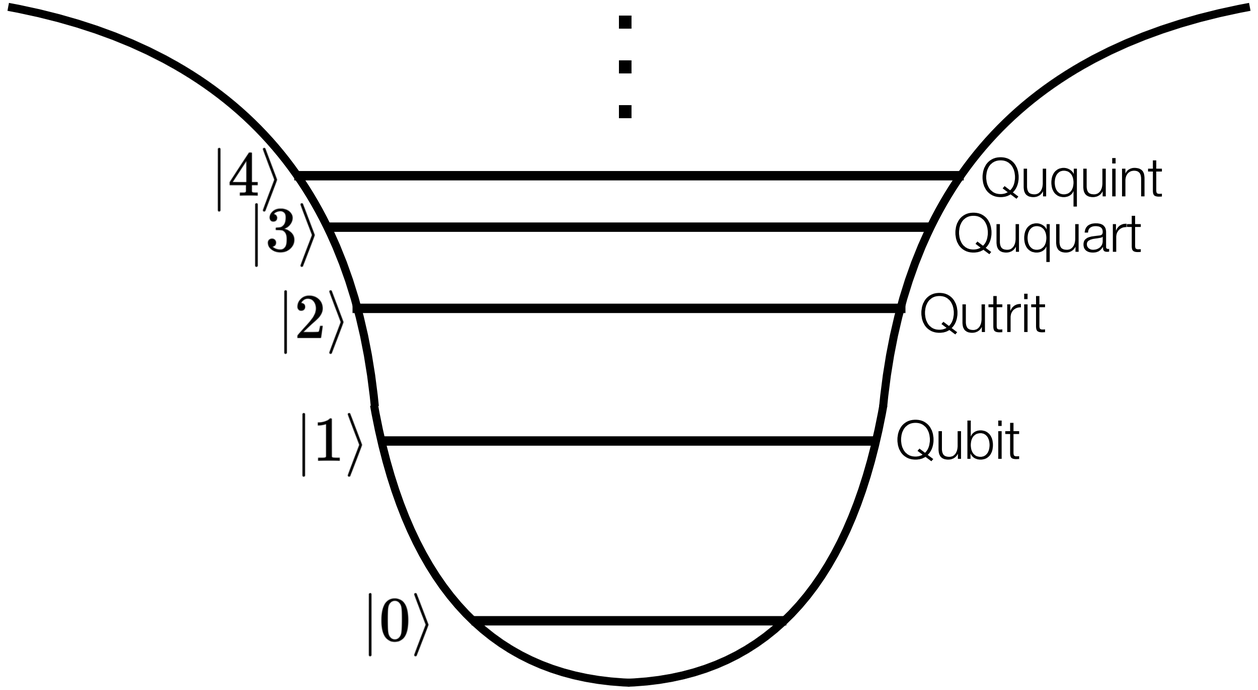
1 Gate, 412 ns

Qubits are Two Level Quantum Devices



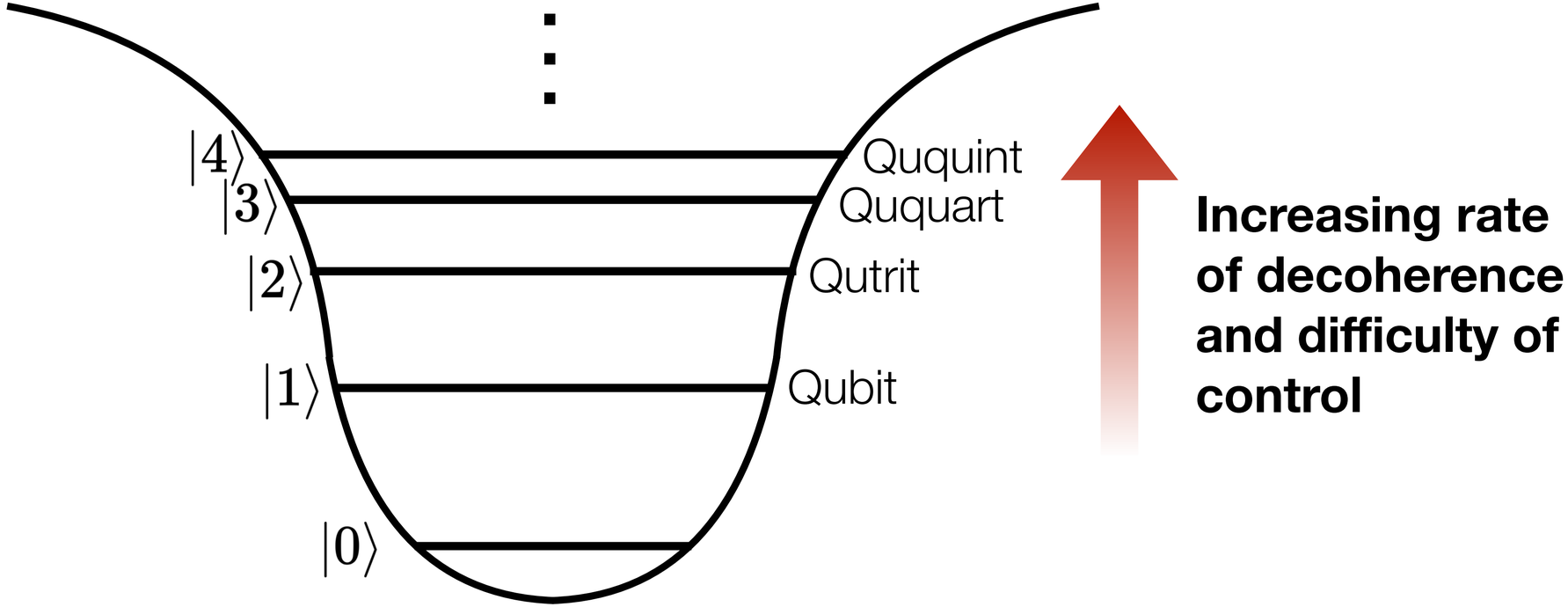
Energy Well Representation of a Quantum Device

Quantum Devices are Not Just Qubits



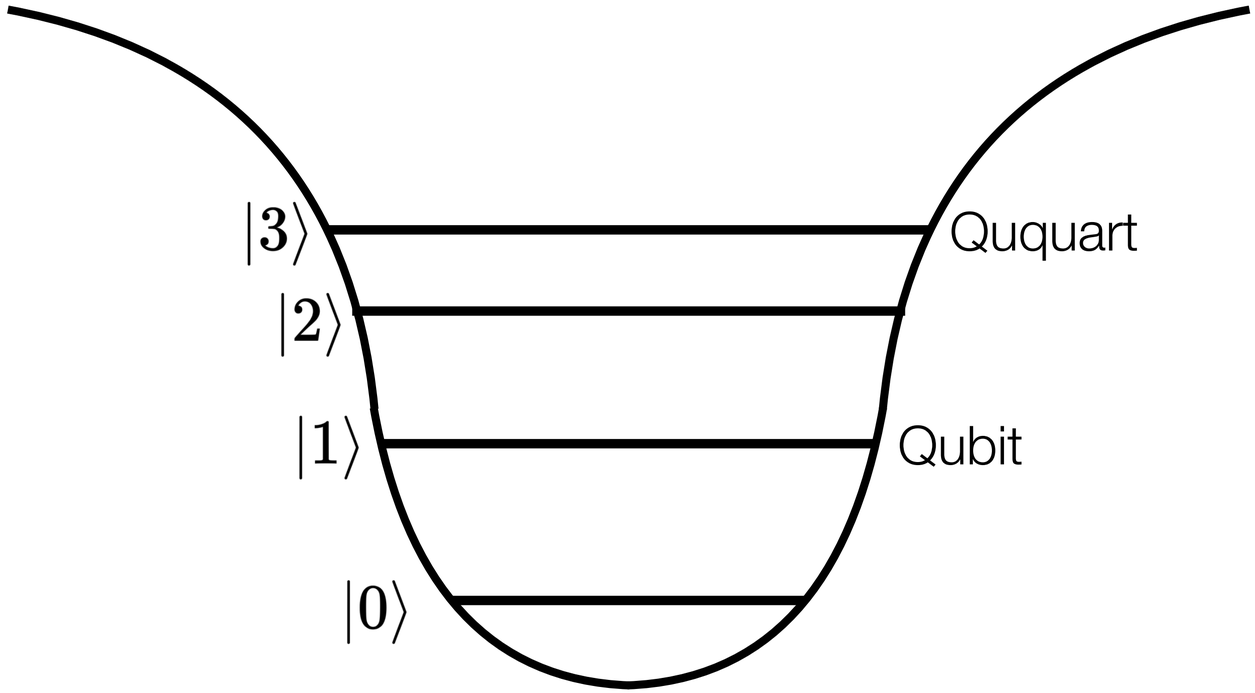
Energy Well Representation of a Quantum Device

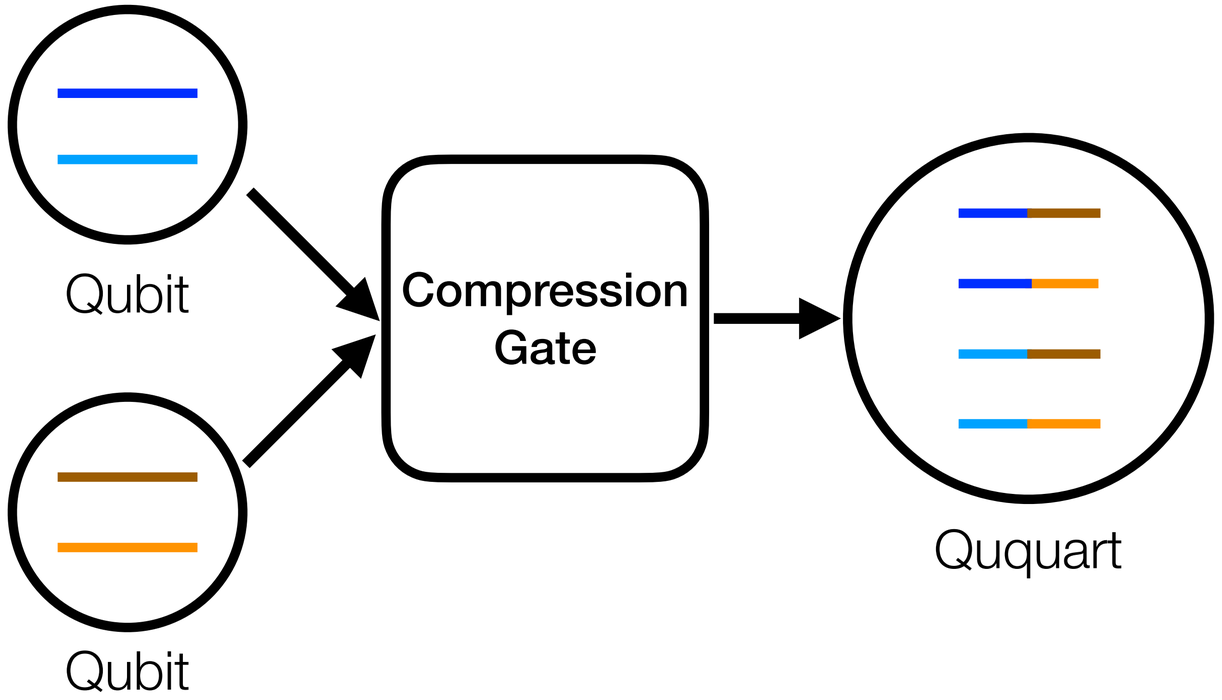
Higher Energies are Harder to Control



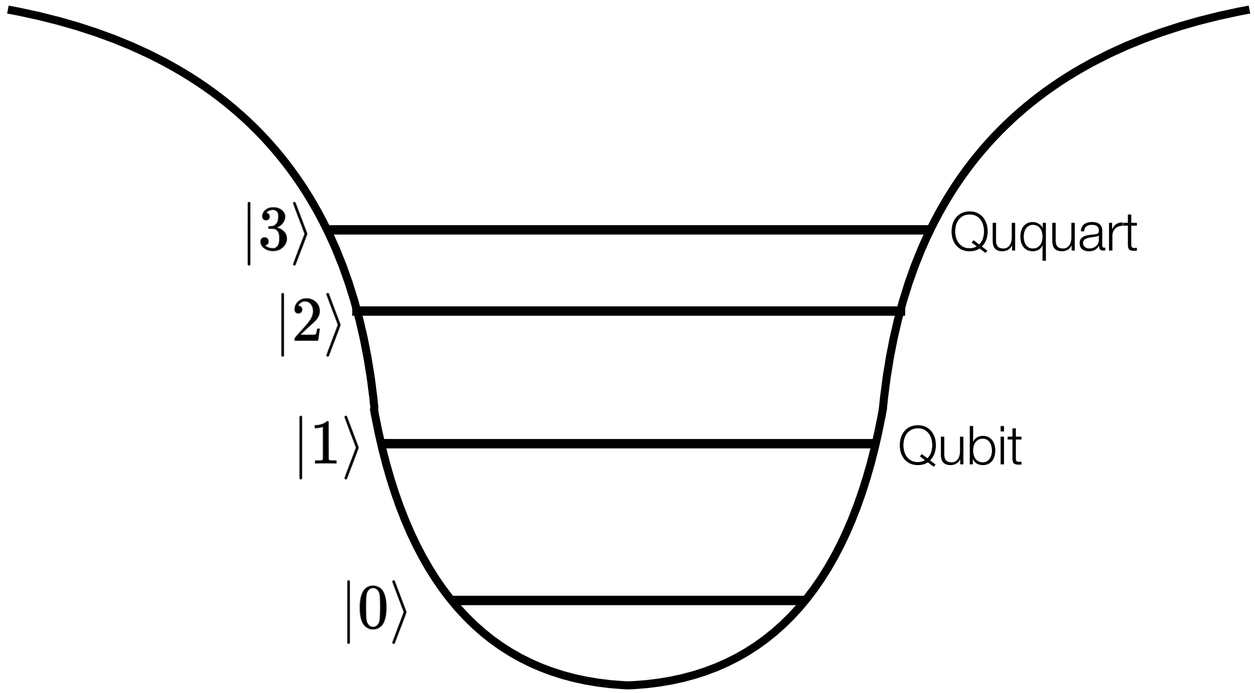
Energy Well Representation of a Quantum Device

One Ququart Can Be Two Qubits

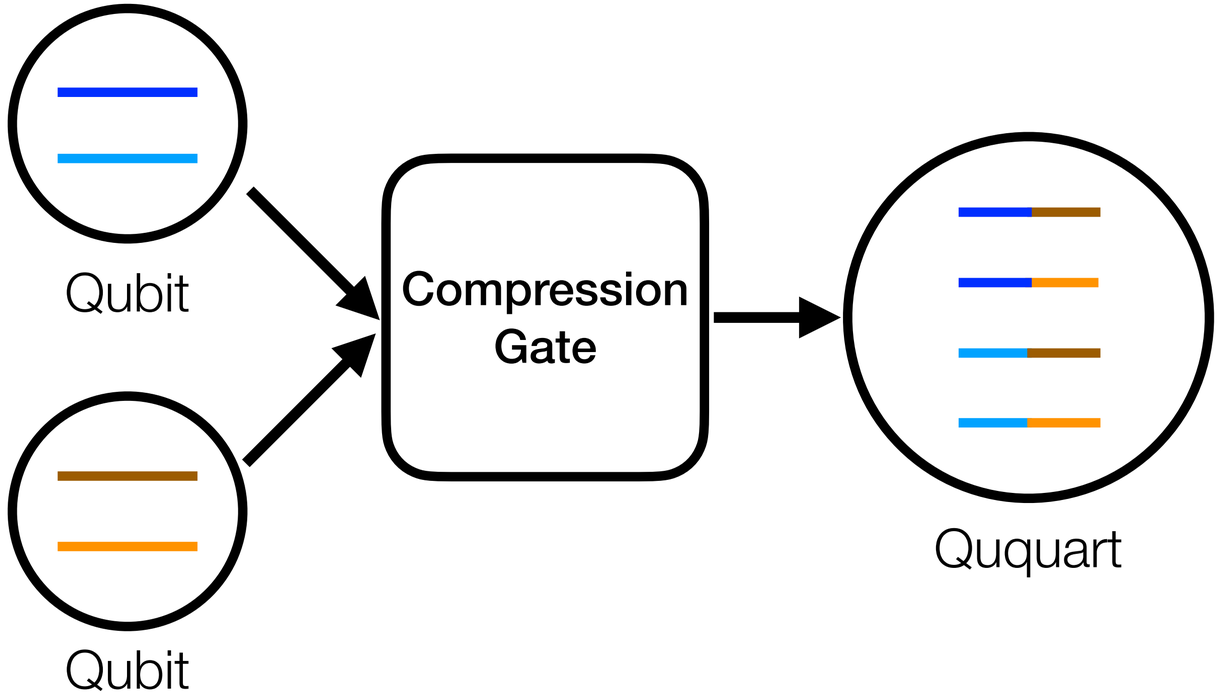




Not as Expensive as Previously Thought



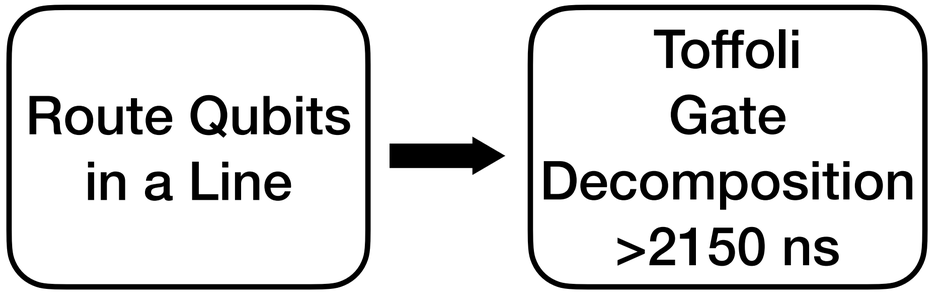
Time-Efficient Qudit Gates through Incremental Pulse Re-seeding
Seifert et al - QCE 2022

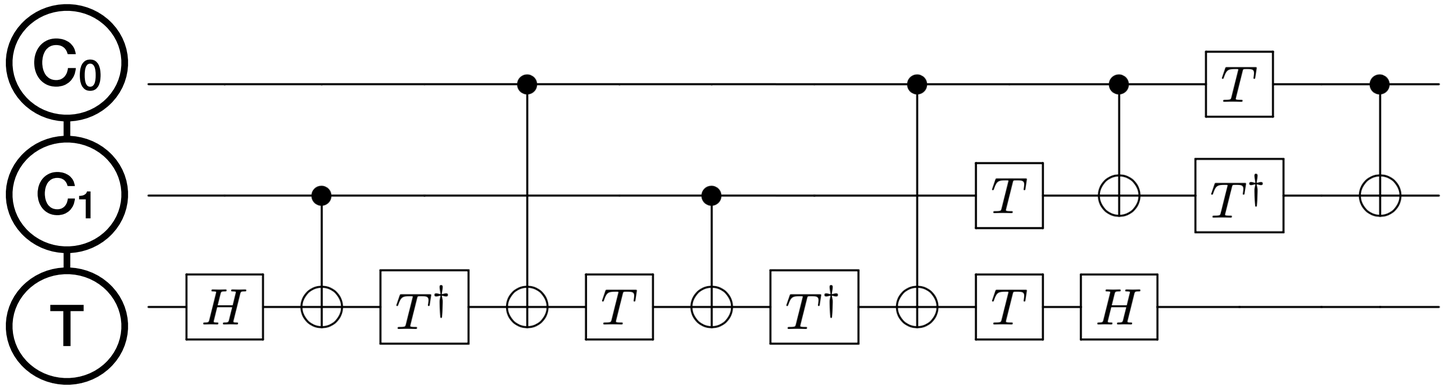


Qompress: Efficient Compilation for Ququarts Exploiting Partial and Mixed Radix Operations for Communication Reduction
Litteken et al - ASPLOS 2023

Compiling With Three Qubit Gates

Traditional (Qubit-Qubit)



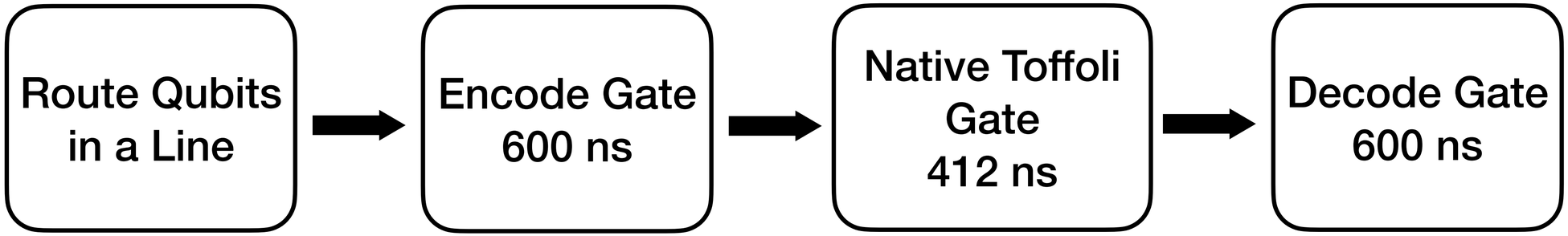


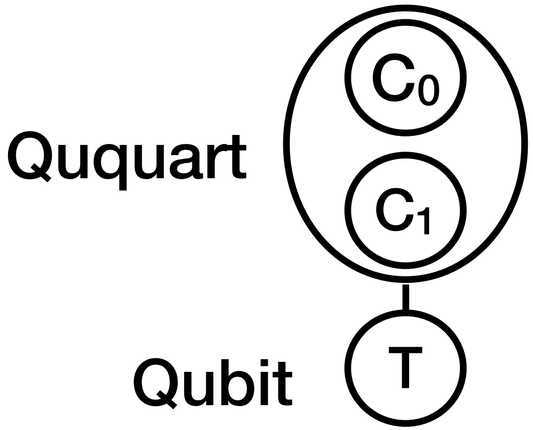
Decomposed Toffoli Gate

14-16 Gates, 2105 ns

Compiling With Three Qubit Gates

Mixed-Radix (Qubit-Ququart)

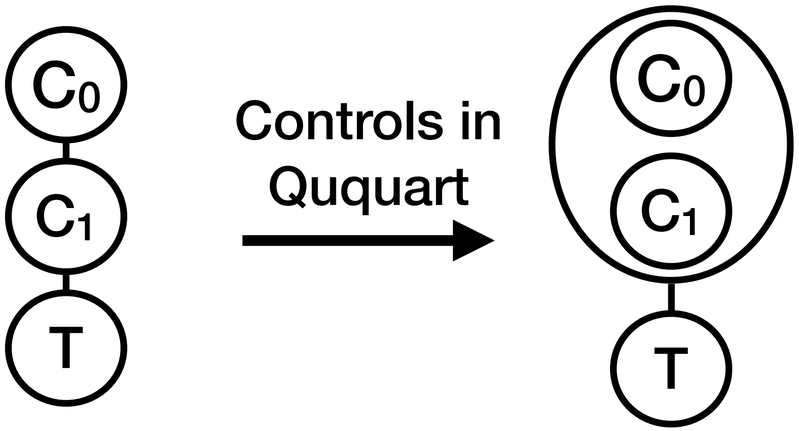




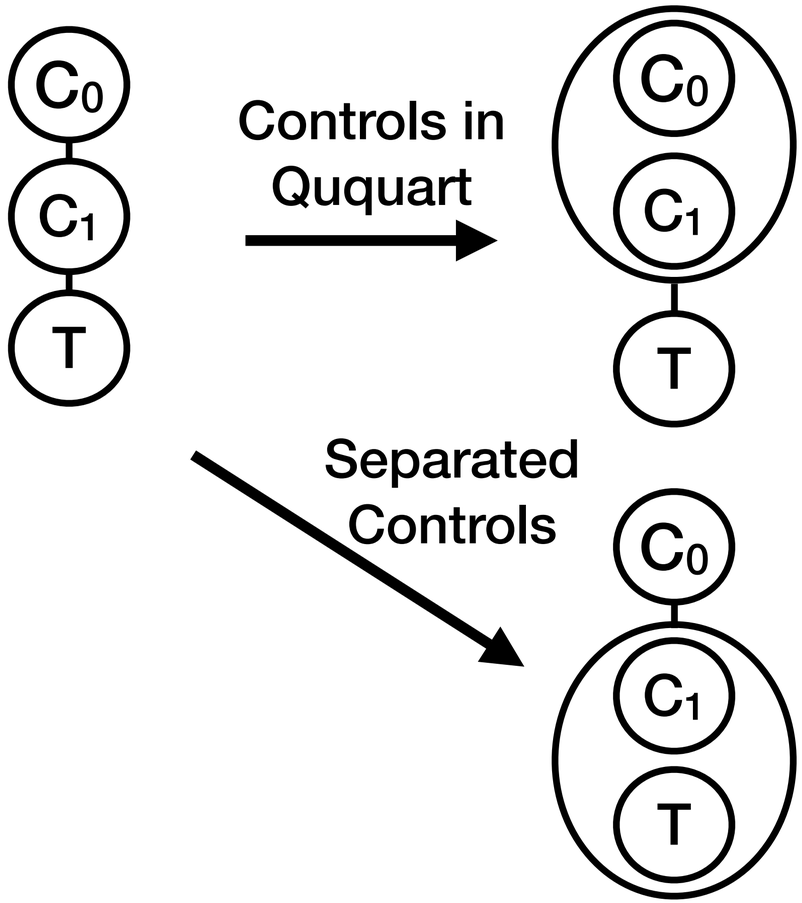
Ququart-Qubit Toffoli Gate

3 Gates, 1612 ns

Mixed-Radix Qubit Configurations Differ



Mixed-Radix Qubit Configurations Differ



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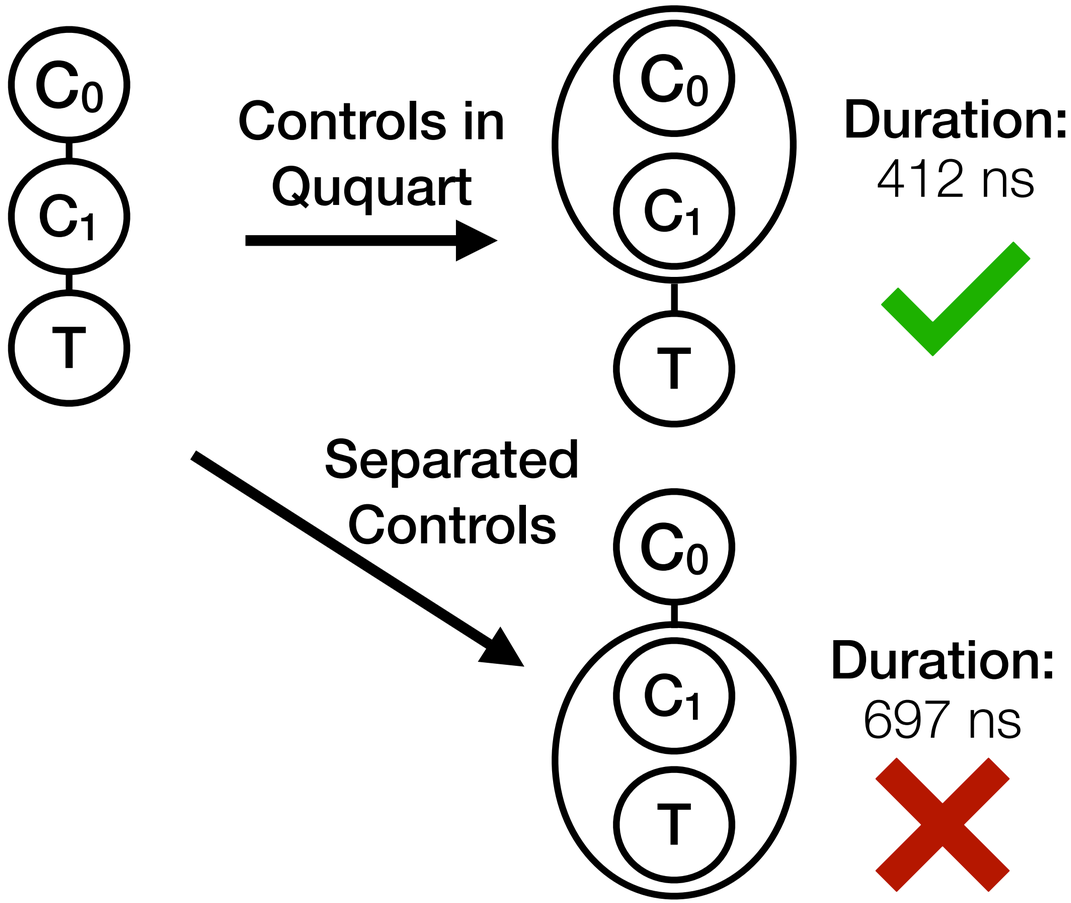

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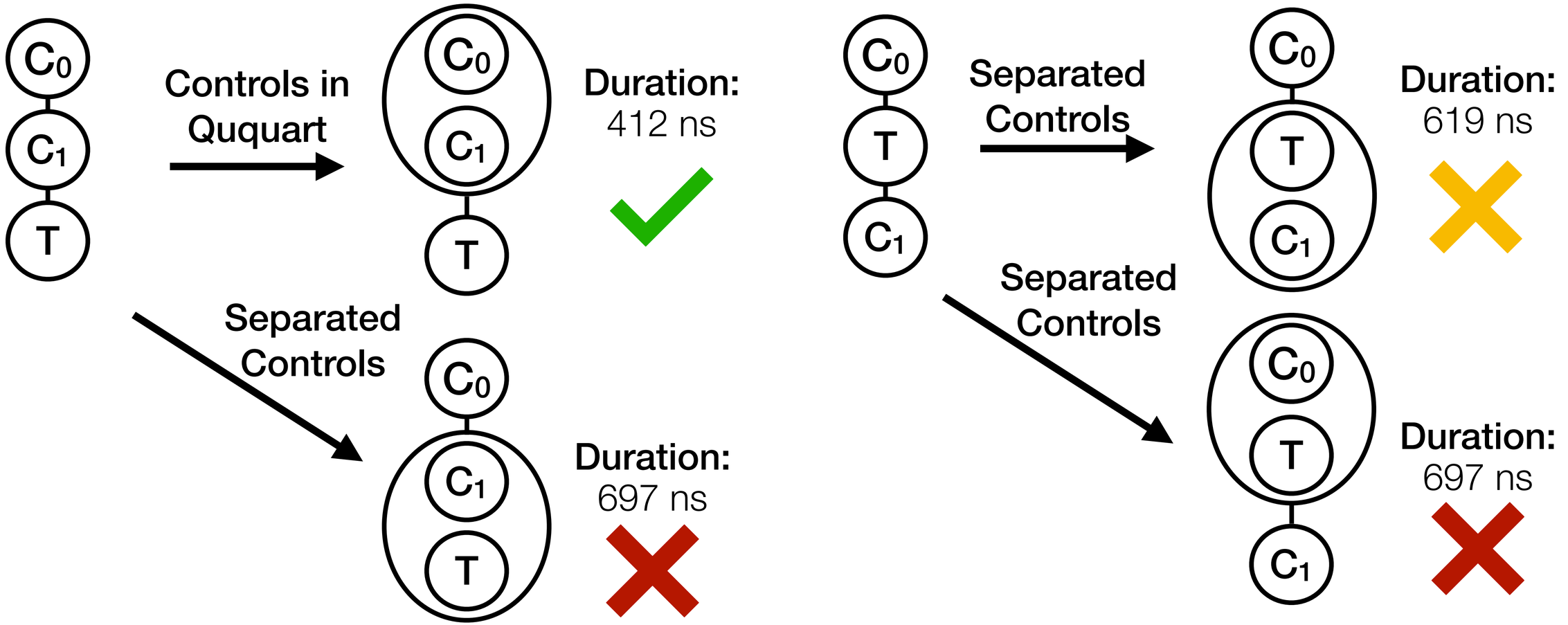
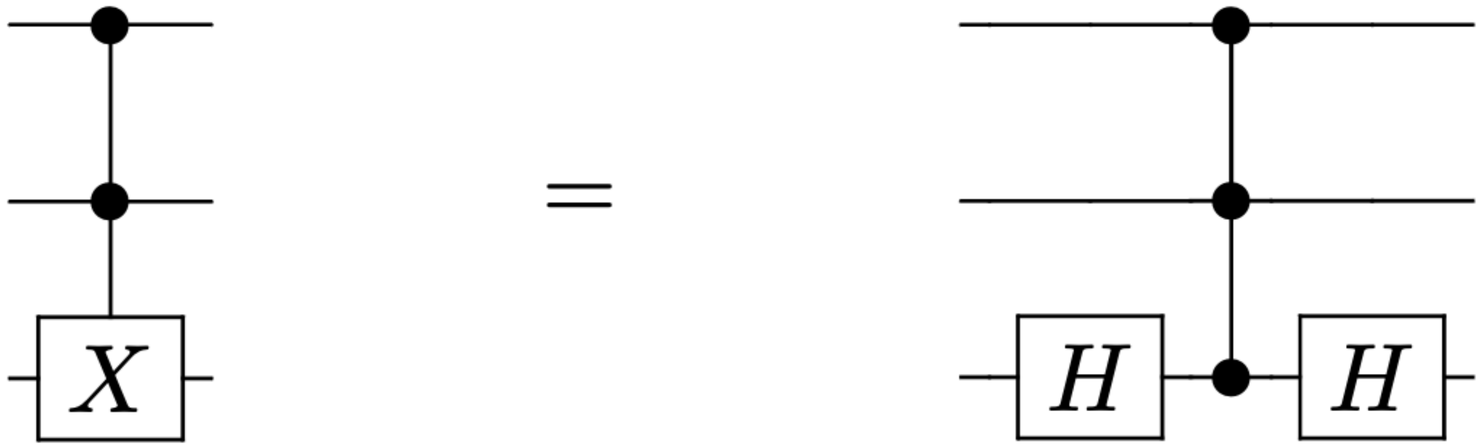


Using the All-Control Case

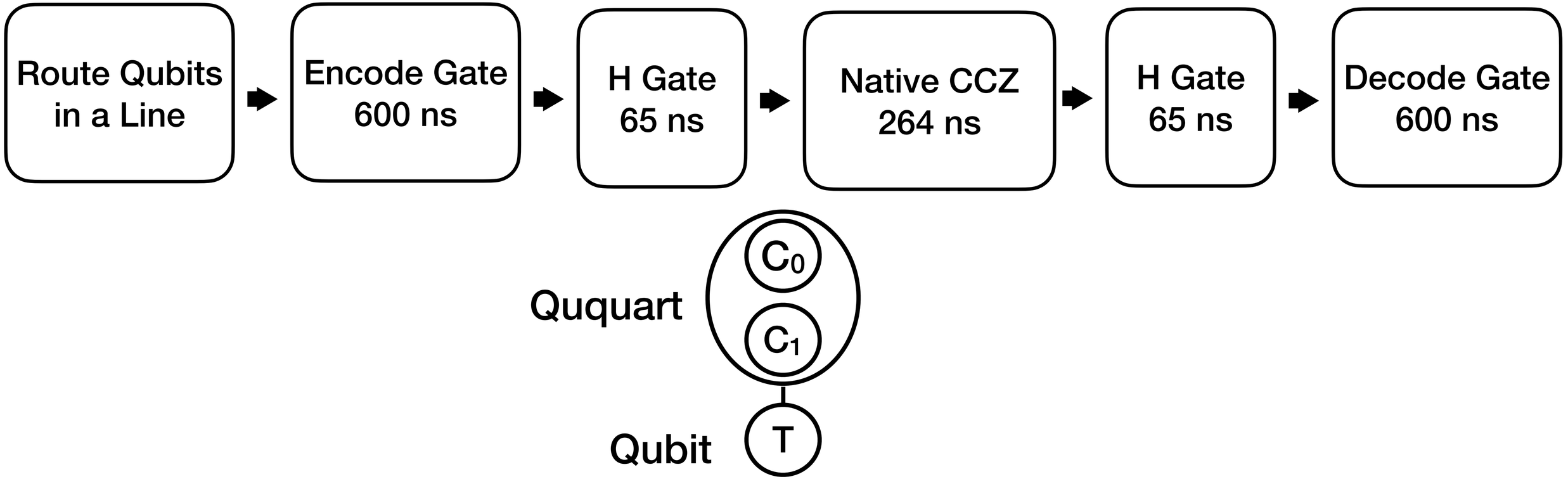


Best Mixed-Radix
Toffoli:
412 ns

Mixed-Radix
Toffoli as CCZ:
264 ns + 2*65 ns = 384 ns

Compiling With Three Qubit Gates

Mixed-Radix (Qubit-Ququart)

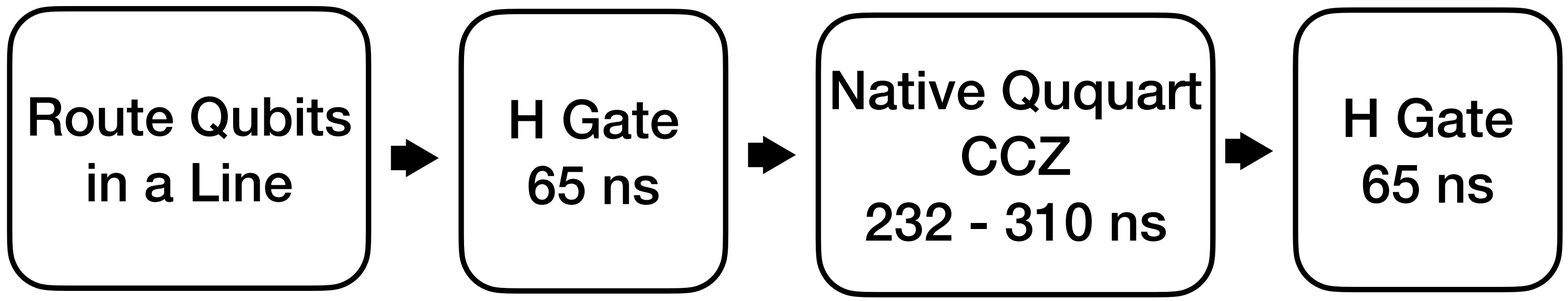


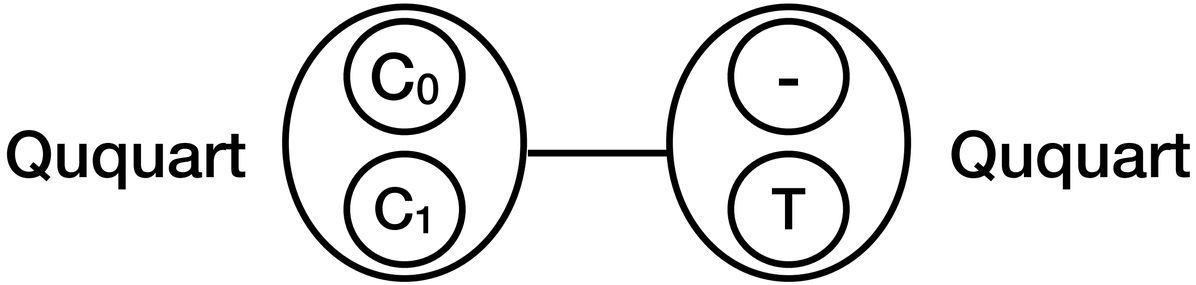
Ququart-Qubit H+CCZ+H Gate

5 Gates, 1594 ns

Compiling With Three Qubit Gates

Full Ququart (Ququart-Ququart)



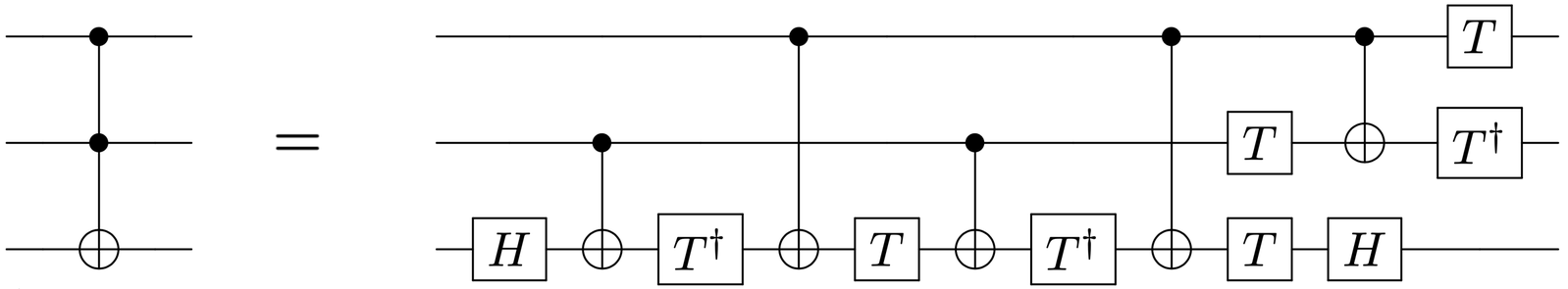


Ququart-Ququart H+CCZ+H Gate

3 Gates, 453 ns, Higher Rate of Decoherence

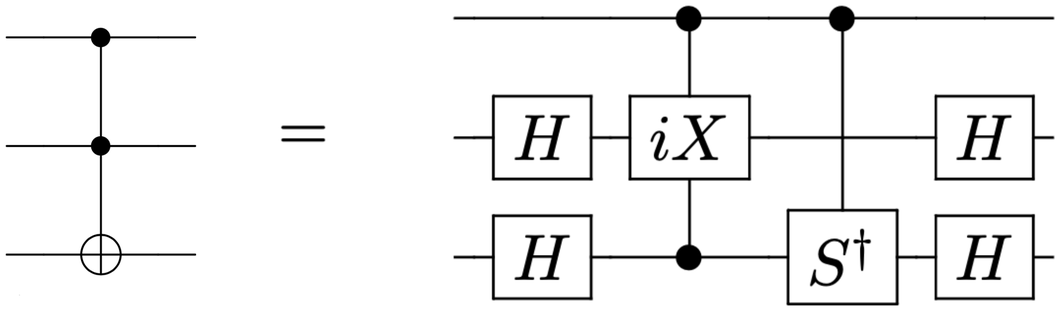
Baselines

Qubit-Only Two-Qubit Gates



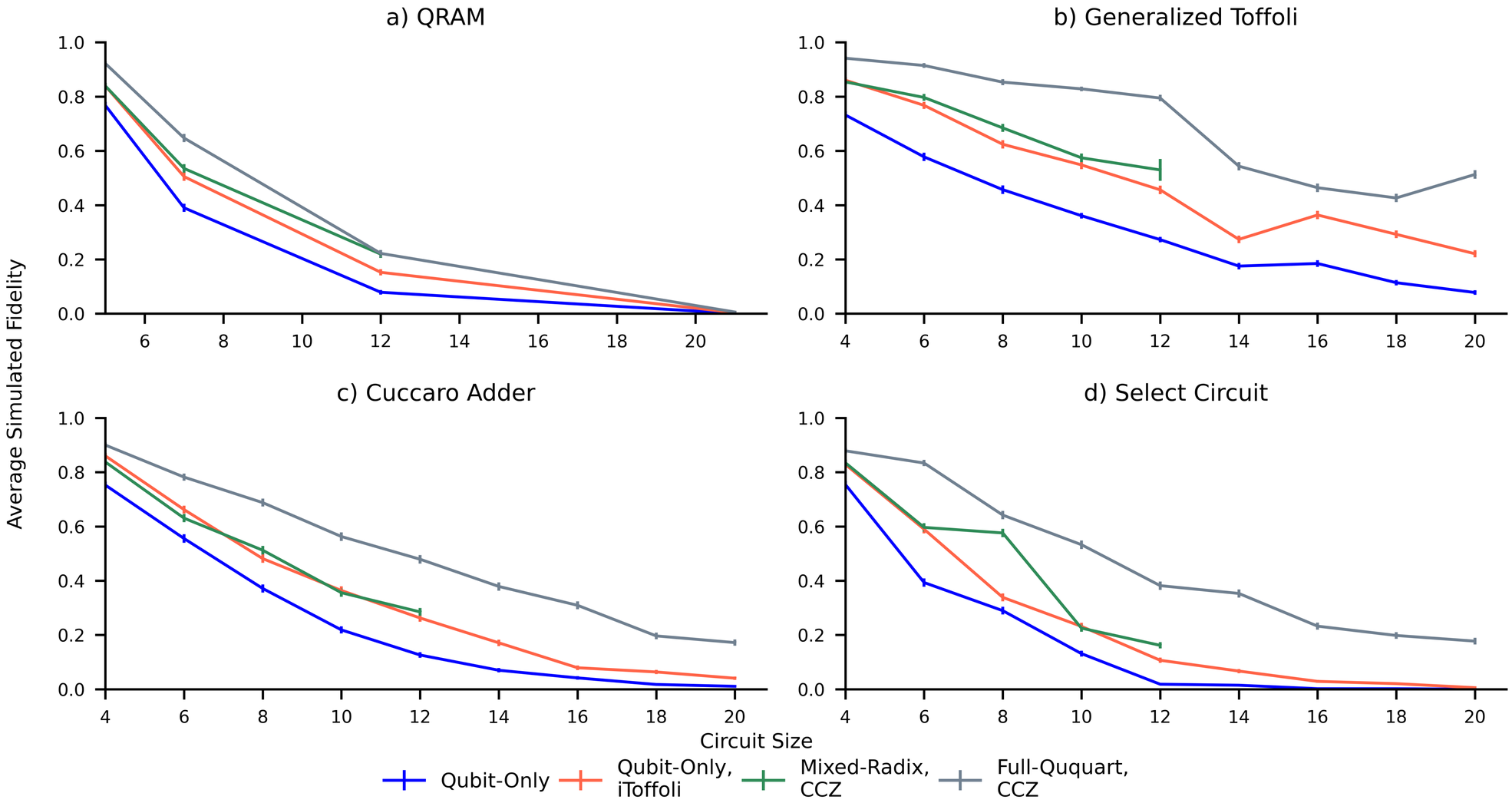
Complete Time:
2105 ns

Qubit-Only iToffoli Three-Qubit Gates

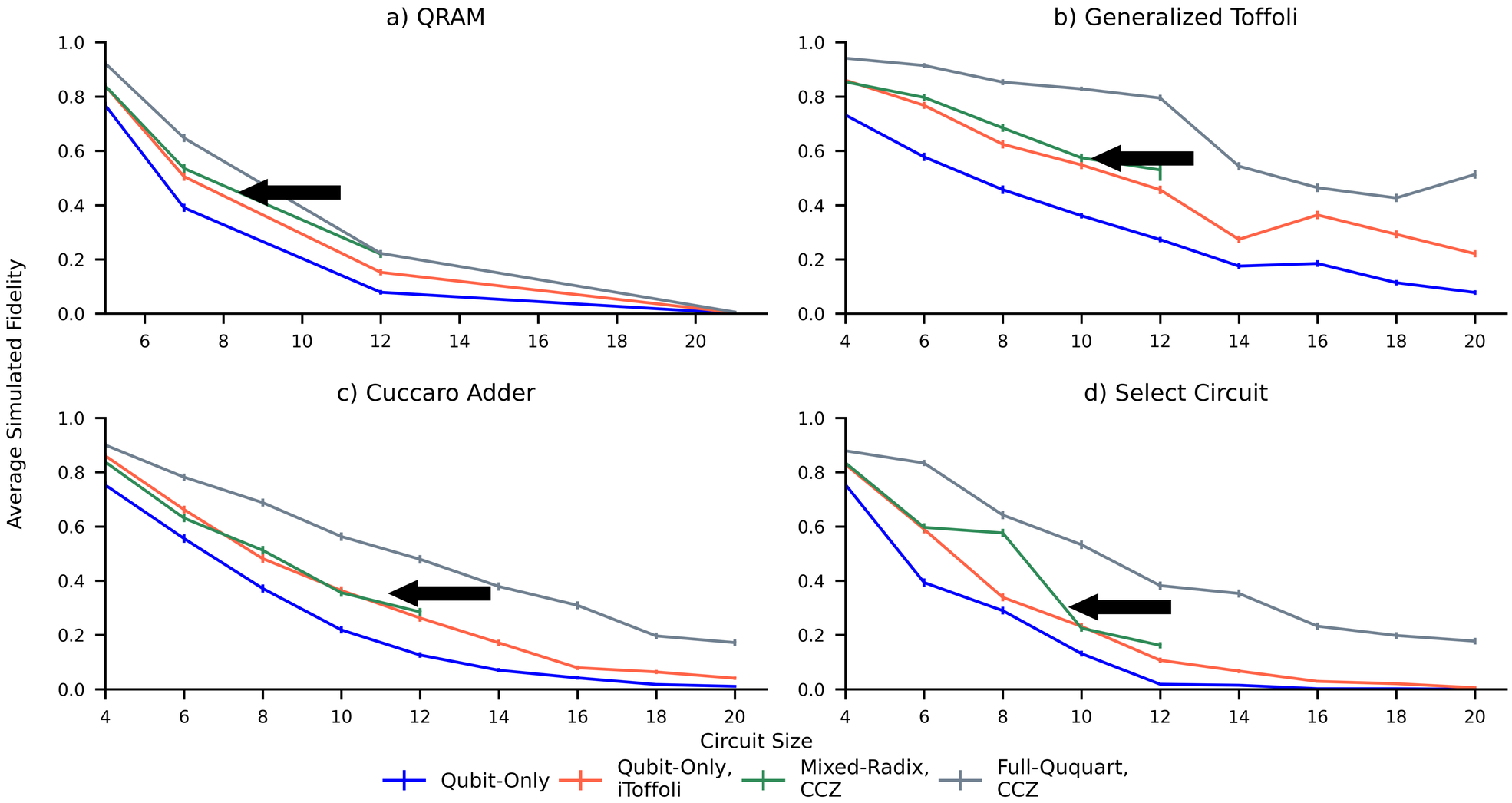


iToffoli Time: 912 ns
Complete Time:1593 ns
Requires Calibration Across
Two Couplers

Results


a) QRAM
b) Generalized Toffoli
c) Cuccaro Adder
d) Select Circuit
Average Simulated Fidelity
Circuit Size
Qubit-Only
Qubit-Only, iToffoli
Mixed-Radix, CCZ
Full-Ququart, CCZ

Results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Qubit-Only, iToffoli
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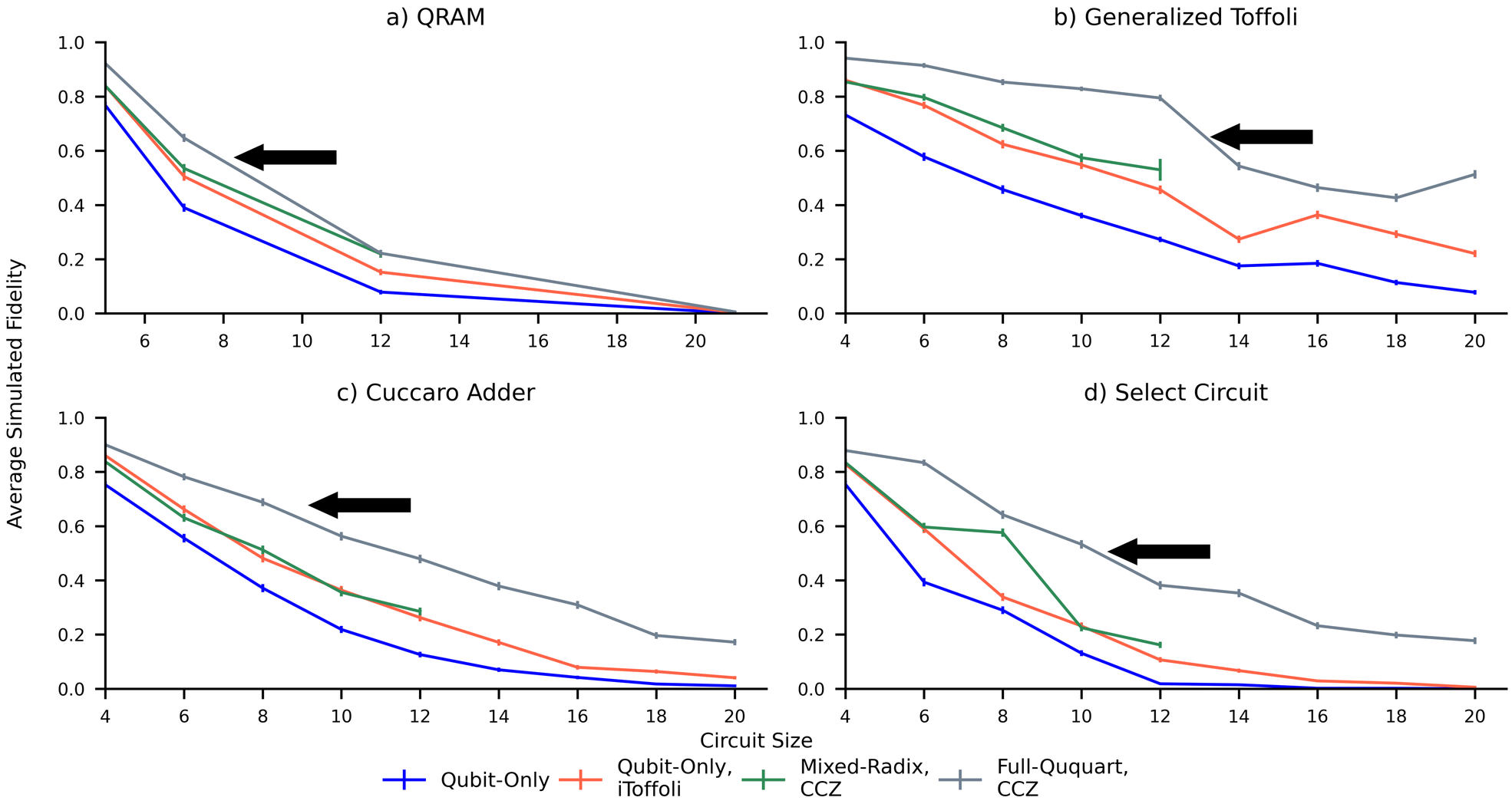
Results

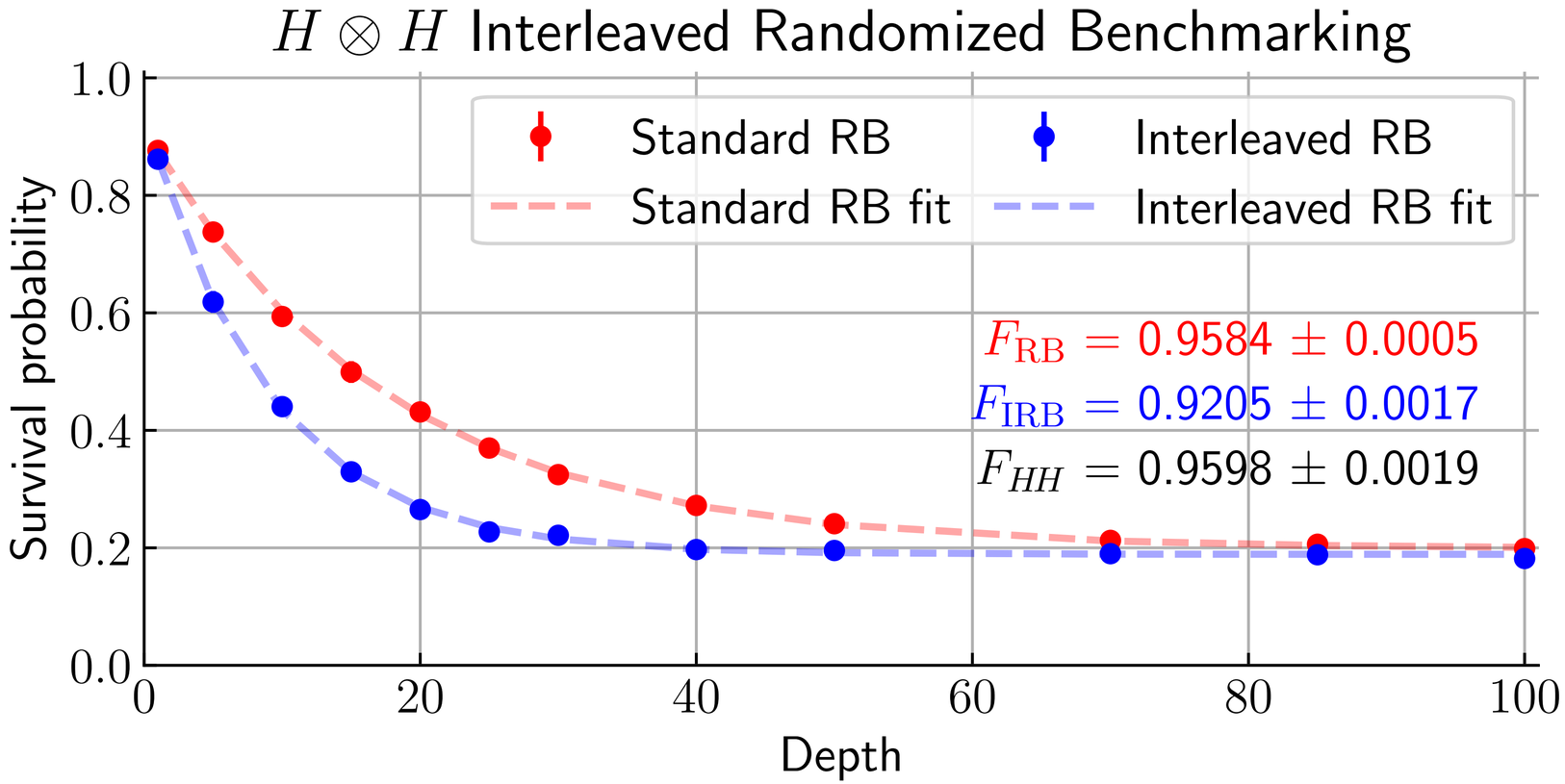

a) QRAM
b) Generalized Toffoli
c) Cuccaro Adder
d) Select Circuit
Average Simulated Fidelity
Circuit Size
Qubit-Only
Qubit-Only, iToffoli
Mixed-Radix, CCZ
Full-Ququart, CCZ

Conclusion

- Higher radix devices open the possibility of native three-qubit gates across a single coupler.
- While configuration matters, the more population changes can be isolated to a single device, the more efficient the gate can be.
- Mixed-radix three-qubit gate decompositions have comparable, or improved, performance to past implementations qubit-only three-qubit gates and can be less logistically complicated to implement.
- Full-ququart gates, in circuits with many three-qubit gates, can further improve the fidelity of qubit-only strategies even in the face of higher rates of decoherence.

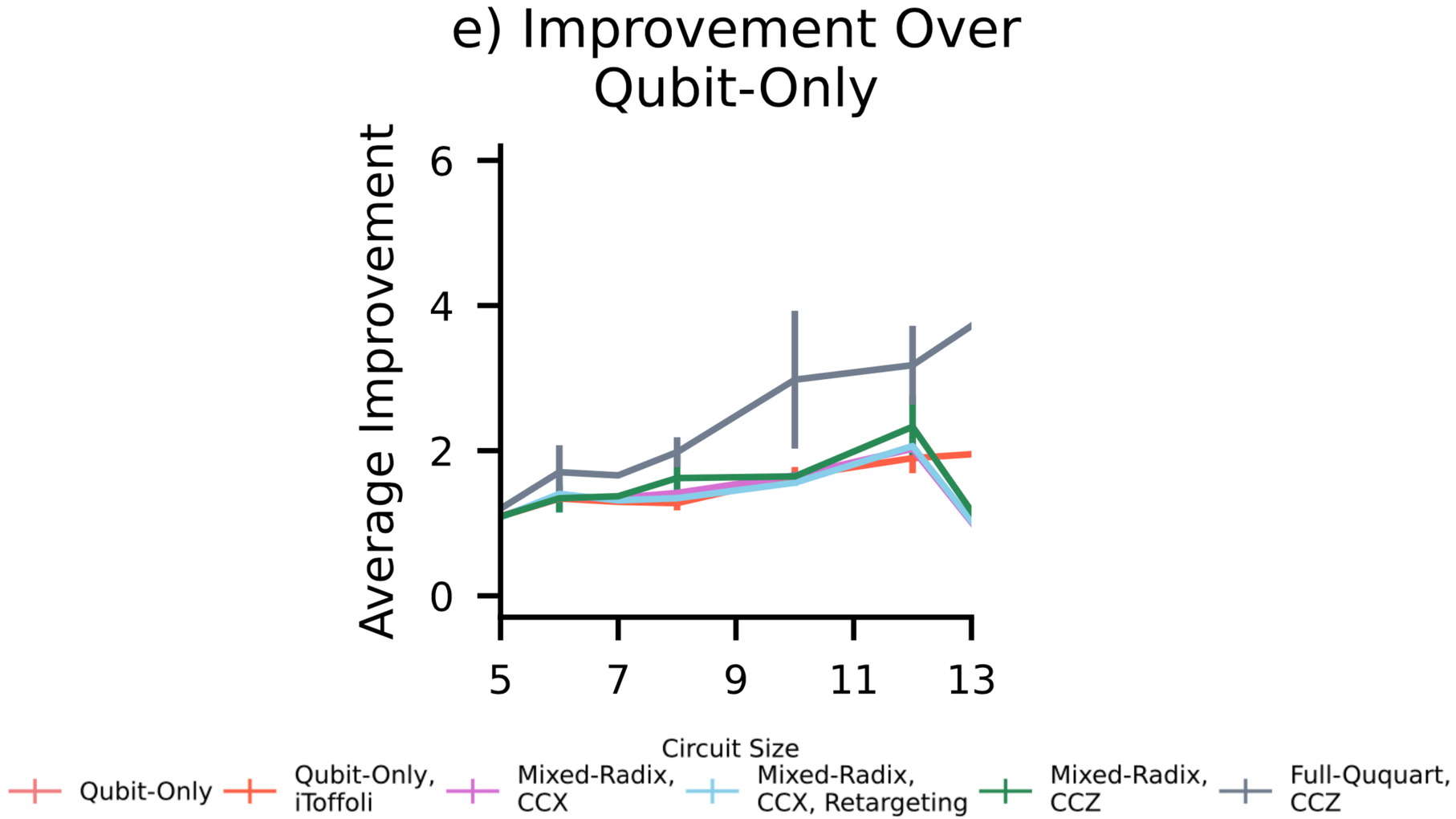
Questions?

Does it Work?

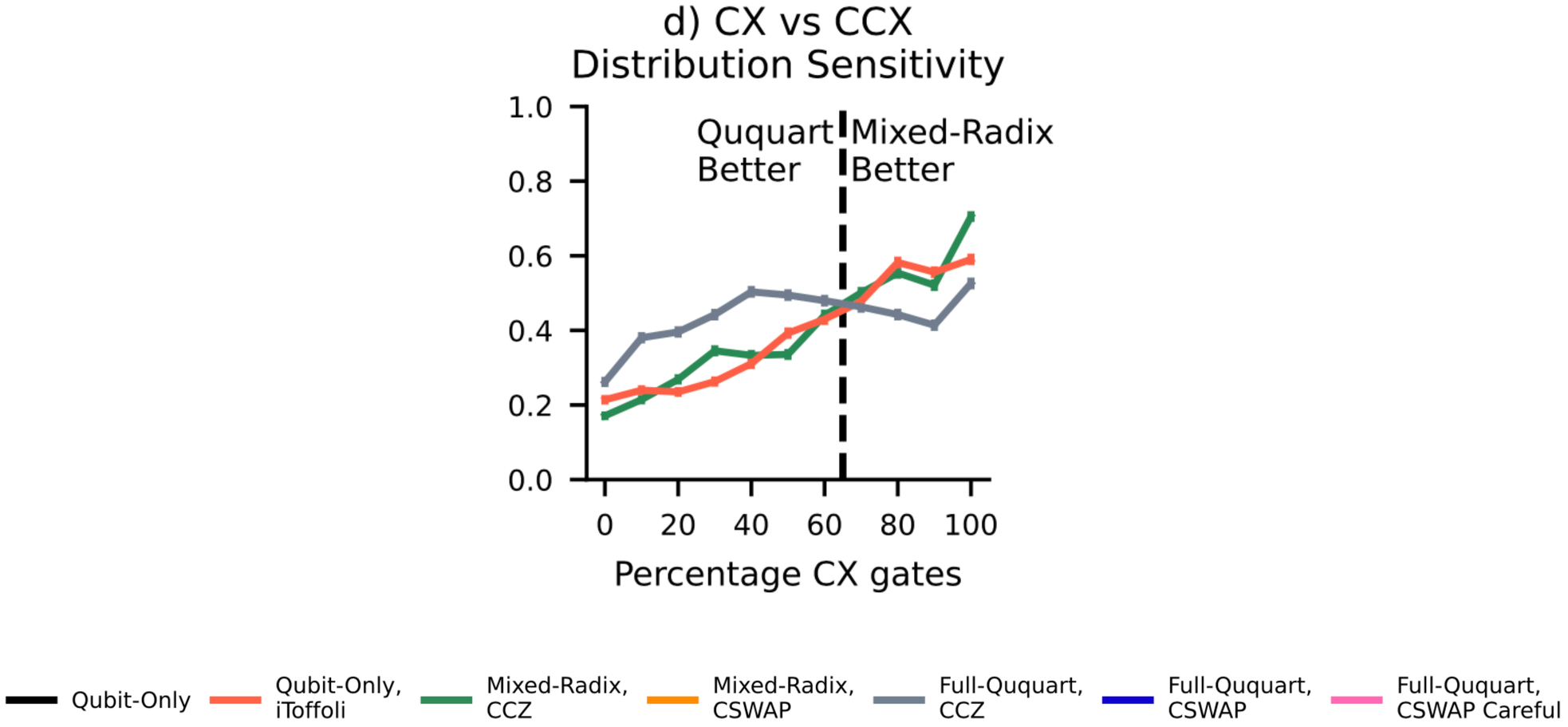


Dancing the Quantum Waltz: https://arxiv.org/abs/2303.14069

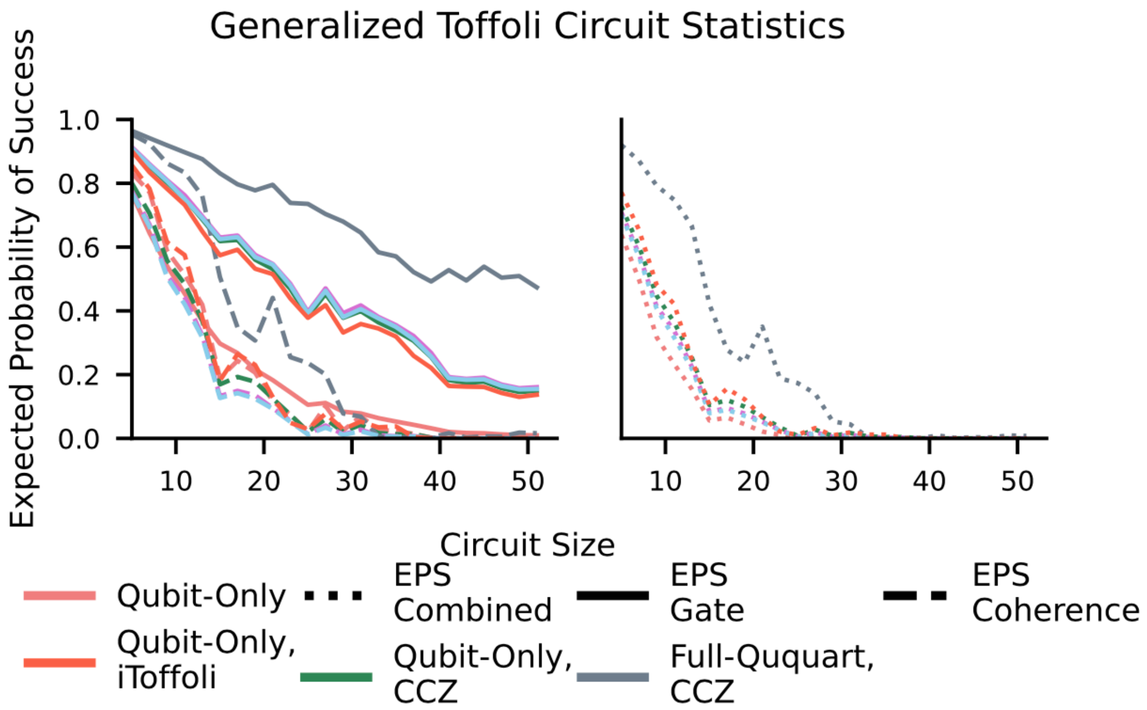
Average Fidelity Improvements



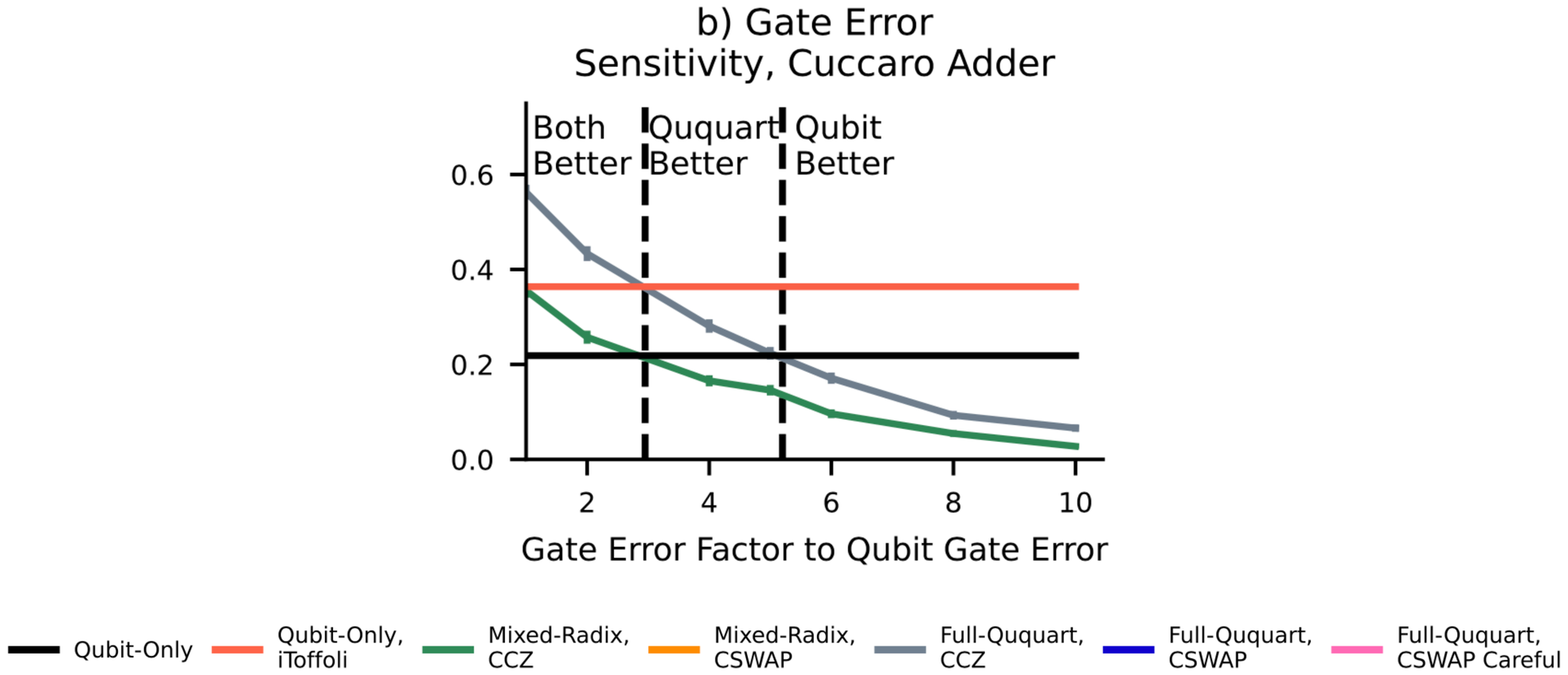
Ratio of Two-Qubit Gates to Three-Qubit Gates



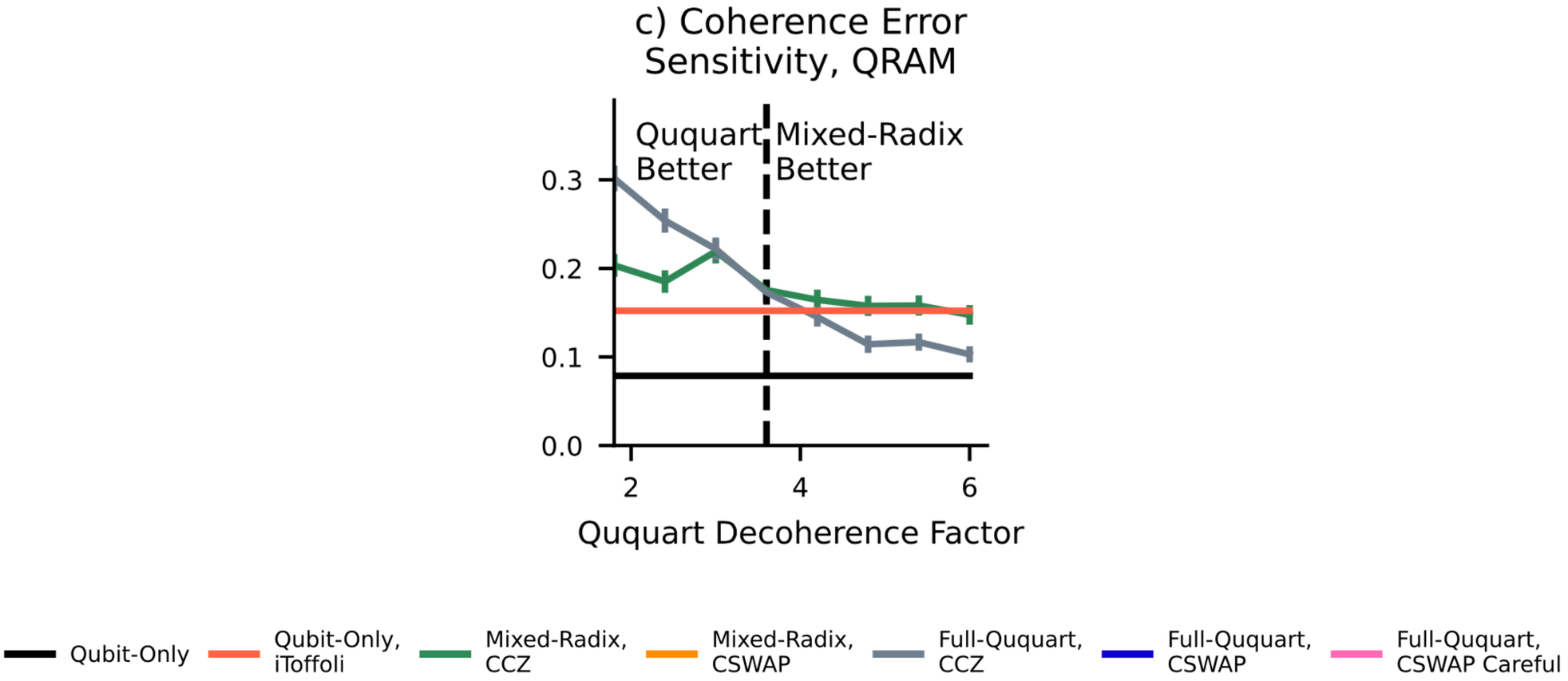
Ongoing Circuit Error Estimation



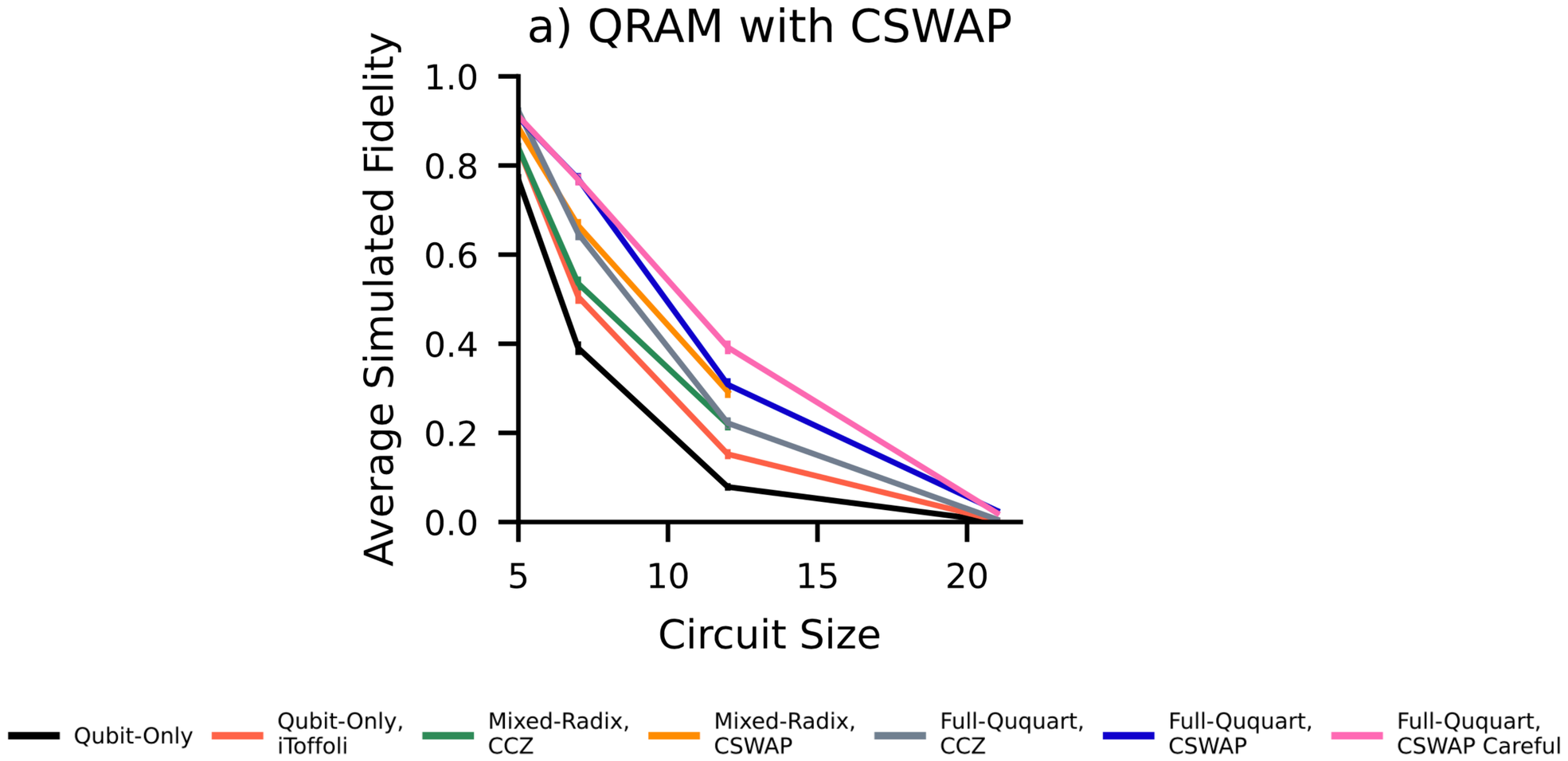
Sensitivity to Gate Error



Sensitivity to Coherence Error



Multi-Target, Not Multi-Control



Random Mappings as a Starting Point