Scalability Evaluation of Quantum Circuit Simulation with Qulacs on Fugaku

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Introduction

Quantum circuit simulation plays a crucial role in developing and validating quantum algorithms on classical supercomputers. However, the exponential state space growth (2^n for n qubits) demands massive computational resources, making large-scale HPC systems indispensable. While previous research demonstrated impressive simulation milestones, comprehensive understanding of how diverse algorithms scale on modern supercomputers remains limited, leaving practitioners without systematic guidance for resource allocation.

Challenges in Quantum Circuit Simulation at Scale

- ❌ **Unknown resource requirements** for different algorithms on large-scale HPC systems
- ❌ **Limited understanding** of how parallelization configuration affects simulation performance
- ❌ **Unclear trade-offs** between execution time, energy consumption, and rank density
- ❌ **No systematic guidance** for practitioners to make informed resource allocation decisions

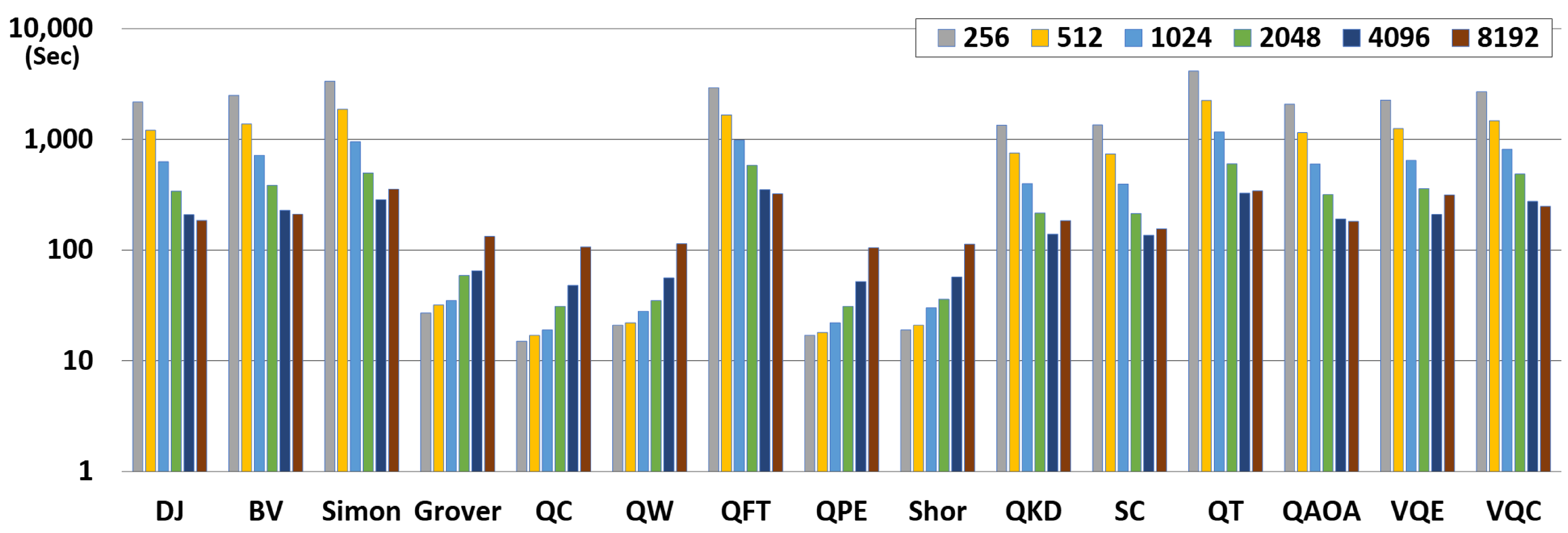
Systematic Evaluations of Various Quantum Algorithms on Fugaku

- ❖ Platform: Fugaku Supercomputer
  - ➢ A64FX processor (48 cores, 32 GB HBM2)
  - ➢ Tofu Interconnect D (6D mesh/torus)
  - ➢ Up to 8192 nodes utilized
- ❖ Evaluation Configurations
  - ➢ Strong Scaling: 256 → 8192 ranks
  - ➢ Rank Density: 1-32 ranks/node
  - ➢ Metrics: Time, power, energy
- ❖ Tools
  - ➢ Q-gen: Quantum circuit generator
  - ➢ mpiQulacs: Parallelized simulator

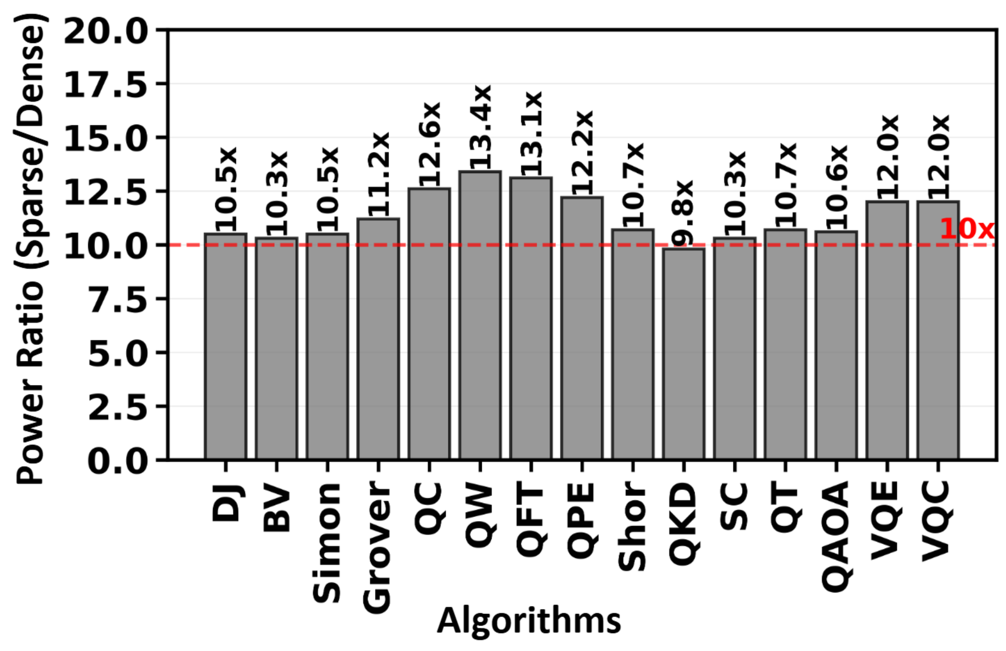
Category	Algorithm	Qubits	Single-qubit gates	Two-qubit gates
Quantum Query	Deutsch-Jozsa (DJ)	35	71	0
	Bernstein-Vazirani (BV)	35	86	18
	Simon's Algorithm (Simon)	36	36	24
Quantum Search	Grover's Algorithm (Grover)	14	40779	40954
	Quantum Counting (QC)	6	1323	891
	Quantum Walk (QW)	11	21874	15124
Quantum Fourier Transform	Quantum Fourier Transform (QFT)	35	1890	1241
	Quantum Phase Estimation (QPE)	11	3225	2151
	Shor's Algorithm (Shor)	18	32677	14532
Quantum Communication	Quantum Key Distribution (QKD)	35	69	0
	Superdense Coding (SC)	35	23	68
	Quantum Teleportation (QT)	36	72	48
Variational Quantum Algorithms	Quantum Approximate Optimization Algorithm (QAOA)	35	105	70
	Variational Quantum Eigensolver (VQE)	35	140	595
	Variational Quantum Classifier (VQC)	35	735	1224

Evaluated quantum algorithms and gate statistics (abbreviations in parentheses)

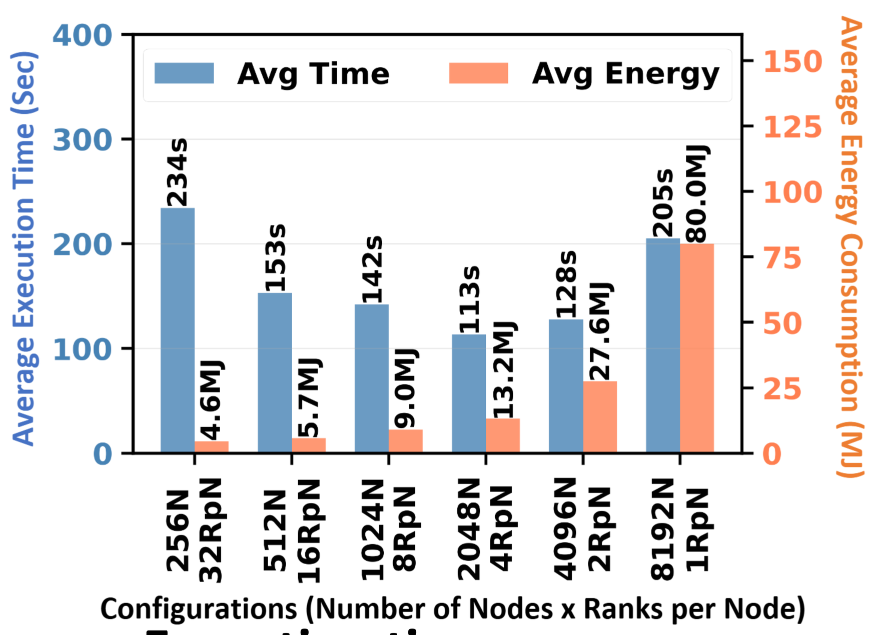
Key Findings and Practical Guidelines



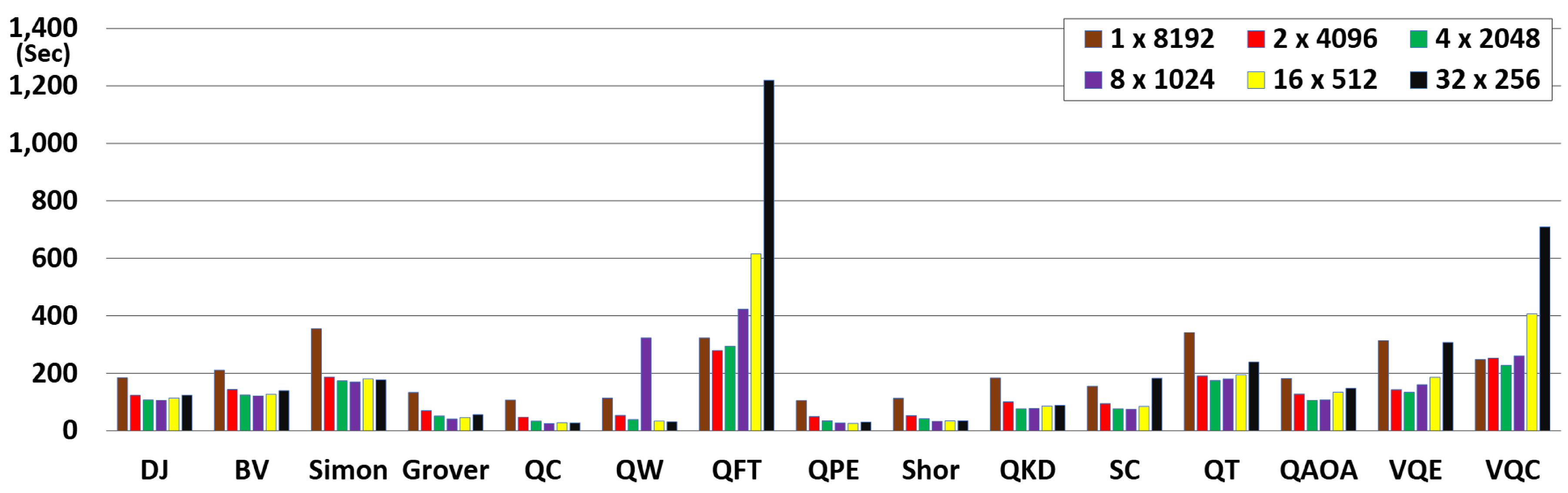
Strong scaling performance of 15 quantum algorithms



Power ratio (sparse/dense deployment)



Execution time vs energy consumption (average values)



Impact of rank density on performance (8192 rank configuration)

- ❖ State vector size determines scaling (not gate count)
  - ➢ Large state vectors (35-36 qubits): 7-12× speedup
  - ➢ Small state vectors (6-18 qubits): Negative scaling
- ❖ Rank density leads to 4× performance variation
  - ➢ QFT: 300s (sparse) → 1200s (dense)
  - ➢ Low-density for QFT/VQC
- ❖ Dense packing offers >10× energy savings
  - ➢ Trade-off: Faster execution vs energy efficiency

Conclusions and Future Work

This study provides practical guidance for quantum circuit simulation on HPC systems. State vector size (not gate count) determines scaling behavior—large state vectors achieve 7-12× speedup while small state vectors show negative scaling. Rank density causes up to 4× performance variation, and dense packing offers >10× energy savings. Future work includes weak scaling evaluation and performance portability across different HPC architectures.

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