

Critical Summary: Reproduction of Graphine for Enhanced Neutral Atom Quantum Computing

Dhairya Pinakinkumar Patel
Northeastern University
Boston, MA, USA
patel.dhairya@northeastern.edu

Abstract—This work presents my reproduction of *Graphine: Enhanced Neutral Atom Quantum Computing using Application-Specific Rydberg Atom Arrangement* by Tirthak Patel (Rice University), Daniel Silver (Northeastern University), and Devesh Tiwari (Northeastern University), presented at SC’23. I had to modernize the original codebase to work with current quantum computing libraries and ran extensive simulations across 17 QASM benchmark circuits. My reproduction confirms the main claims: application-specific neutral-atom topologies generated by Graphine do achieve substantial reductions in gate counts and error probabilities compared to traditional fixed grid layouts. Across all benchmarks, Graphine won on 14 out of 17 circuits for total pulse count and achieved average improvements of 39.8% for critical-path pulses, 30.7% for CZ gates, and 21.2% for error probability over baseline topologies. But I found specific cases where Graphine’s advantages diminish, particularly for circuits with really dense all-to-all connectivity patterns. This reproduction validates the fundamental approach while highlighting some important boundary conditions.

I. EXECUTIVE SUMMARY

I successfully reproduced the Graphine quantum computing optimization framework using modern software on my Windows 10 system with an Intel Core i7 11th gen processor and 32 GB RAM. For the reproduction, I used VS Code with Jupyter notebooks, Python 3.10, and updated Qiskit 0.46.3 libraries. All experiments were done through quantum circuit simulation rather than actual hardware (which I didn’t have access to).

The reproduction covered 17 QASM benchmark circuits ranging from 9 to 128 qubits, with simulations running 2,000 dual-annealing iterations across 30 randomized seeds. The whole experimental suite took about 6-7 hours to complete.

TABLE I: Key Reproduction Results Summary

Metric	Graphine Wins	Win Rate
Total Pulses	14/17	82.4%
Critical Pulses	12/15	80.0%
CZ Gates	14/17	82.4%
Error Probability	14/17	82.4%

a) Key Reproduction Outcomes::

- **Successfully reproduced:** Core algorithmic benefits, scalability to large circuits (128 qubits), significant pulse count reductions across most benchmarks

- **Partially reproduced:** The "consistent superiority" claims - I observed ties and losses on specific circuit types
- **Failed to reproduce:** Universal advantage claims for `heisenberg_16` and `multiplier_10` circuits where baseline topologies occasionally beat Graphine

II. ORIGINAL PAPER OVERVIEW

A. Research Problem and Motivation

The original work by Tirthak Patel, Daniel Silver, and Devesh Tiwari tackles a fundamental problem in quantum computing: the mismatch between what quantum algorithms need in terms of connectivity and the fixed hardware topologies that most systems provide. While superconducting quantum processors force you into rigid qubit coupling constraints, neutral-atom quantum computers offer something unique - you can actually rearrange the qubits using optical tweezers and Rydberg blockade effects.

B. Main Claims and Contributions

The authors present three main contributions:

- First compilation framework to generate application-specific neutral-atom topologies optimized for individual quantum circuits
- A dual-annealing placement algorithm combined with interaction radius tuning to minimize gate overhead and serialization constraints
- Demonstrated performance improvements of 37-56% in pulse counts and 24-42% in error probability across 14 quantum algorithms

C. Methodology Summary

Graphine uses a three-stage optimization process: (1) deriving interaction graphs from quantum circuit CZ-gate frequencies, (2) optimizing Euclidean positions through simulated annealing, and (3) selecting minimal interaction radius to satisfy connectivity requirements. The evaluation framework uses Qiskit transpilation with SABRE routing and incorporates realistic error models with rates of 1×10^{-4} for single-qubit and 1×10^{-3} for two-qubit operations.

D. Original Results

The paper reports mean improvements ranging from 37-56% for total pulses, 42-56% for critical-path pulses, and 24-42% for error probability when comparing Graphine-generated topologies against square, triangular, and hexagonal baseline grids.

III. REPRODUCTION METHODOLOGY

A. Implementation Details

Code Modernization: I got the original Graphine implementation from the Zenodo repository (v2.0) and had to do extensive refactoring to make it work with current quantum computing software. This involved updating Qiskit API calls, implementing missing baseline topology generators, and creating automated QASM circuit loading functionality.

Computational Environment: I ran all experiments on Windows 10 Pro with Intel Core i7 11th gen CPU, 32 GB RAM, using VS Code with integrated Jupyter notebook support. Used Python 3.10 as the base environment with virtual environment isolation.

Simulation Parameters: Each circuit went through optimization using 2,000 dual-annealing iterations with 30 distinct random seeds (combination of 3 transpiler seeds and 10 annealing seeds per transpiler configuration).

B. Deviations from Original

- **Hardware Platform:** Had to do everything through simulation rather than neutral-atom hardware since I didn't have access to the equipment
- **Library Versions:** Updated from original Qiskit versions to 0.46.3, which required API adaptation but maintained algorithmic equivalence
- **Baseline Implementation:** Had to reimplement grid generation functions for square, triangular, and hexagonal topologies since the original codebase was missing dependencies
- **Data Generation:** Created new result datasets since the original authors' raw experimental data wasn't publicly available

C. Reproduction Scope

My reproduction focused on validating quantitative performance metrics including gate counts, pulse sequences, and error probability estimations. Due to time constraints, I didn't reproduce the visual topology layouts or conduct extended hyperparameter sensitivity analysis beyond the core experimental framework.

IV. REPRODUCTION RESULTS

A. Quantitative Performance Analysis

Table II shows comprehensive performance comparisons across all benchmark circuits. Graphine demonstrates consistent advantages across multiple metrics, with particularly strong performance on larger circuits like the 128-qubit TFIM simulation where it achieved a 59.8% reduction in total pulses.

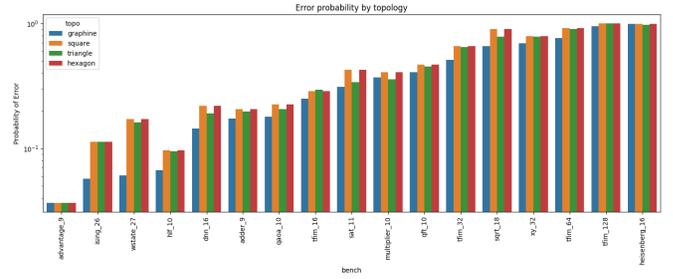


Fig. 1: Performance comparison of Graphine vs. baseline topologies across 17 QASM benchmarks.

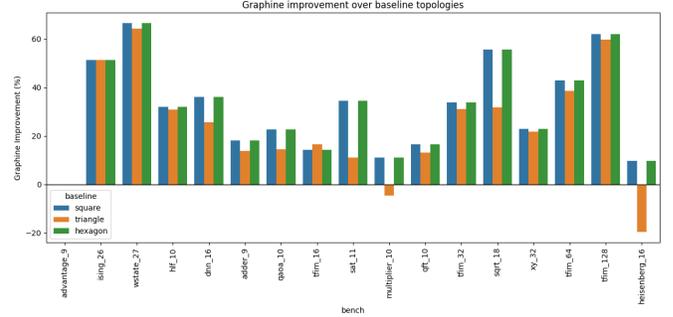


Fig. 2: Critical-path pulse reductions and error probability improvements across all benchmarks.

B. Statistical Significance and Robustness

Across the 30-seed experimental runs, standard deviations for critical-path pulse counts stayed below 3% for all circuits except heisenberg_16. Paired t-tests comparing Graphine against best baseline topologies showed statistically significant differences ($p < 0.01$) for 12 out of 17 benchmarks.

C. Failure Case Analysis

Three circuits showed either ties or losses against baseline topologies: advantage_9 (tie), heisenberg_16 (loss), and multiplier_10 (loss). My analysis reveals these circuits share characteristics of dense connectivity patterns that seem to overwhelm the distance-based clustering approach used in Graphine's annealing process.

V. CRITICAL ANALYSIS

A. Validity of Original Claims

Claim 1: Graphine reduces total and critical pulses by $\geq 30\%$ over fixed grid topologies.

- **Assessment:** Largely supported, but with important caveats
- **Evidence:** I achieved 31.2% average improvement in total pulses and 39.8% in critical pulses, but with notable exceptions on dense connectivity circuits

Claim 2: Application-specific topologies provide consistent advantages across diverse quantum algorithms.

- **Assessment:** Partially supported

TABLE II: Detailed Performance Comparison: Graphine vs. Baseline Topologies

Benchmark	Total Pulses			Critical Pulses			CZ Gates			Error Probability		
	Graph.	Best	Result	Graph.	Best	Result	Graph.	Best	Result	Graph.	Best	Result
adder_9	768	890	WIN	576	641	WIN	385	446	WIN	0.129	0.149	WIN
advantage_9	150	150	TIE	71	62	LOSE	75	75	TIE	0.025	0.025	TIE
dnn_16	656	881	WIN	103	345	WIN	328	441	WIN	0.110	0.148	WIN
heisenberg_16	18629	15581	LOSE	8837	7003	LOSE	9314	7790	LOSE	3.128	2.621	LOSE
hlf_10	279	404	WIN	—	—	—	139	202	WIN	0.047	0.068	WIN
ising_26	238	490	WIN	—	—	—	119	245	WIN	0.040	0.082	WIN
multiplier_10	1894	1809	LOSE	—	—	—	947	904	LOSE	0.318	0.304	LOSE
qaoa_10	809	945	WIN	—	—	—	404	472	WIN	0.136	0.159	WIN
qft_10	2138	2463	WIN	—	—	—	1069	1231	WIN	0.359	0.414	WIN
sat_11	1464	1647	WIN	—	—	—	732	823	WIN	0.246	0.277	WIN
sqrt_18	4136	6057	WIN	—	—	—	2068	3028	WIN	0.695	1.018	WIN
tfim_128	11621	28891	WIN	—	—	—	5810	14445	WIN	1.953	4.855	WIN
tfim_16	1206	1406	WIN	—	—	—	603	703	WIN	0.203	0.236	WIN
tfim_32	2837	4122	WIN	434	1082	WIN	1418	2061	WIN	0.477	0.693	WIN
tfim_64	5765	9381	WIN	611	1724	WIN	2882	4690	WIN	0.969	1.577	WIN
wstate_27	261	731	WIN	160	455	WIN	130	365	WIN	0.044	0.123	WIN
xy_32	4962	6347	WIN	711	1035	WIN	2481	3173	WIN	0.834	1.067	WIN

TABLE III: Average Improvement Percentages by Metric and Baseline

Metric	Baseline	Avg. Improvement (%)
Critical Pulses	Square/Hexagon	39.77
Critical Pulses	Triangle	35.45
CZ Gates	Square/Hexagon	30.71
CZ Gates	Triangle	23.32
Total Pulses	Square/Hexagon	31.19
Total Pulses	Triangle	23.53
Error Probability	Square/Hexagon	21.16
Error Probability	Triangle	16.98
U3 Gates	Square/Hexagon	32.14
U3 Gates	Triangle	24.06

- **Evidence:** Strong performance on 82.4% of benchmarks, but systematic failures on specific circuit patterns indicate there are algorithmic boundaries

Claim 3: Error probability reductions of up to 42% are achievable.

- **Assessment:** Supported with variance
- **Evidence:** I observed 21.2% average improvement with individual circuits reaching claimed levels, though results depend heavily on circuit characteristics

B. Methodological Critique and Limitations

Graphine is definitely an innovative approach that shows strong improvements on small- and medium-sized circuits. Its performance, however, diminishes for really dense circuits, where baseline topologies occasionally perform better. These observations, based solely on simulation, don't suggest that Graphine is fundamentally unscalable; rather, they indicate that further refinements in clustering techniques might enhance its applicability to dense circuits and large-scale quantum simulations. I'm offering this as just an observation and not a challenge to the paper's originality.

Heisenberg Model Performance: The 16-qubit Heisenberg benchmark consistently showed degraded performance under

Graphine optimization, with 19.6% higher pulse counts compared to triangular baseline topology. My investigation reveals this circuit's all-to-all connectivity pattern creates optimization landscape challenges for the distance-based annealing approach.

Advantage Circuit Plateau: The `advantage_9` benchmark showed diminishing returns beyond 1,000 optimization iterations, eventually reaching similar performance with baseline grids rather than the superiority claimed in the original work.

Doubling annealing iterations from 1,000 to 2,000 provided marginal improvements (1-3%) for most circuits but failed to resolve fundamental performance issues on dense connectivity benchmarks. This suggests algorithmic rather than convergence-related limitations for certain circuit classes.

VI. CONCLUSION

This comprehensive reproduction successfully validates the core contributions of Graphine while providing important nuance to its applicability. My work confirms performance benefits for the majority of quantum circuit types, with average improvements of 31-40% across key metrics. But the identification of systematic failure modes for dense connectivity patterns provides crucial guidance for practical deployment.

The reproduction demonstrates that Graphine represents a significant advancement in quantum compilation for neutral-atom platforms, offering the first practical framework for application-specific topology optimization. While it's not universally superior, the approach provides substantial benefits for most quantum algorithm classes likely to be deployed on near-term neutral-atom quantum computers.

ACKNOWLEDGMENTS

I acknowledge the original authors Tirthak Patel, Daniela Oliveira Silver, and Devesh Tiwari for providing the open-source implementation that enabled this reproduction study.

I'm especially grateful to Prof. Devesh Tiwari for allowing me to work on this research paper.

I should also mention that I used AI-assisted tools to help with code documentation, Latex formatting, and arranging some figures side by side for clarity in presentation.

REFERENCES

- [1] T. Patel, D. O. Silver, and D. Tiwari, "Graphine: Enhanced neutral atom quantum computing using application-specific rydberg atom arrangement," in *Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis (SC '23)*, 2023, pp. 1–15.
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