Rethinking Circuit Optimization in FTQC:
Cross-Layer Cost-Aware Optimization for FTQC Circuits

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Motivation

- FTQC involves deep and complex cross-layer compilation stacks
- Logical metrics do not reflect real execution cost
- Single-metric optimization is insufficient, FTQC is inherently multi-objective
- Optimization depends on different FTQC protocols and architectures

FTQC Compilation and Execution Stack

Algorithm
Shor | Grover | HHL | QSP/QSVT | QAOA | VQE

Logical Circuit / IR
Clifford+T Decomposition | **Circuit Optimization** | Unitary Synthesis

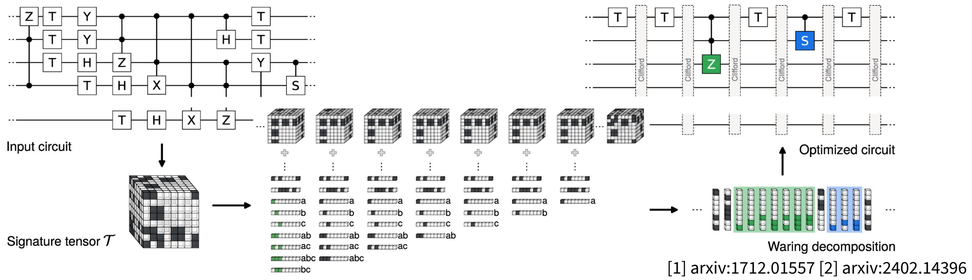
Fault-tolerant Program Realization

Fault-tolerant Gate Constructions	Architecture-specific Operations	Physical Gate Mappings
Surface Code: Lattice Surgery	Superconducting: Joint Parity Measurement	Surgery / Braiding Scheduling
Color Code: Transversal Clifford	Neutral Atom: Transversal CNOT	Magic State Factory Placement
Code Switching	Trapped Ion: All-to-all Connectivity	Measurement Ordering
Magic-State Cultivation	Photonic:	Routing Resolution

Classical Control
Syndrome Extraction | Decoding | Feed-forward Correction | Pauli Frame Tracking

T-only circuit optimization

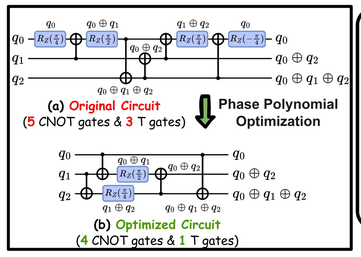
- Exploit algebraic structure to compress the phase tensor into a lower-rank representation using a decoding-based method[1].
- Use reinforcement learning to search over circuit transformations to discover lower-rank tensor representations(which can lead to fewer T gates)[2].

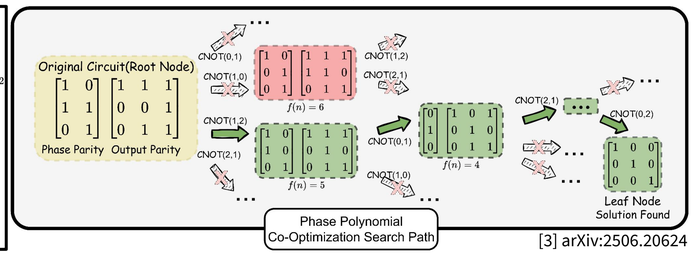


[1] arxiv:1712.01557 [2] arxiv:2402.14396

CNOT-only optimization

- CNOT-Phase circuit can be efficiently represented using *Phase Polynomials IR*.
- *PhasePoly*[3] using heuristic search to transform the parity table with fewer steps.

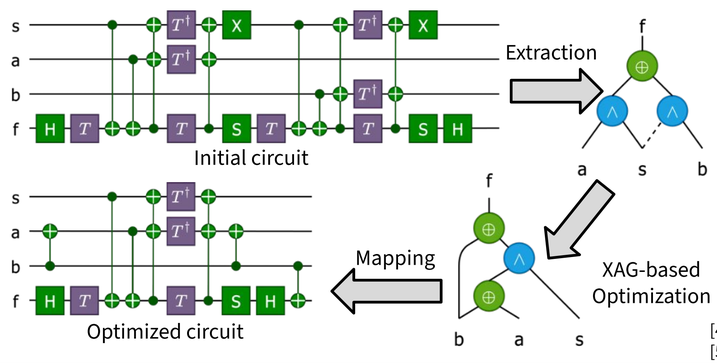




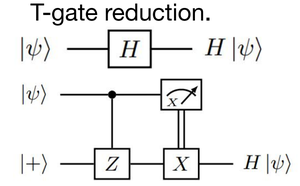
[3] arXiv:2506.20624

Ancilla-needed optimization

- XAG-based synthesis[4] rewrites circuits into XOR-AND structures to reduce T gates via algebraic simplification and ancilla-assisted decomposition.

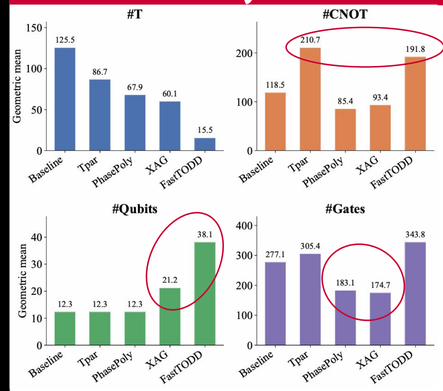


- By turning H into ancilla-based gadgets[5], enabling deeper restructuring and further T-gate reduction.



[4] npj Quantum Information 8.1 (2022): 7.
[5] arXiv:2407.08695

Key Observations



- **Tpar**: only *T* optimization
- **PhasePoly**: CNOT optimization with rotation merging
- **XAG**: XAG-based *T* optimization(DAC26)
- **FastTODD**: *T* optimization with H gadgets

Unoptimized baseline consists of 24 diverse circuit benchmarks, each bar shows the Geo Mean for the corresponding metric.

Error-correction protocols and architecture-specific cost model

- Different QECCs (surface code, qldbc, color code…)
- Magic State Factory vs Magic State Cultivation
- Lattice Surgery CNOT vs Transversal CNOT
- Ancilla-Rich vs Qubit-Limited Regimes
- 2D Color Code {H, S, CNOT} vs 3D Color Code {CZ, CCZ, CNOT, T}
- Superconducting vs Non-Local Architectures (Ion Trap / Neutral Atom)

Key Takeaways

- Need cross-layer IR to enable holistic, end-to-end optimization
- Need multi-objective cost modeling beyond single-gate reduction
- Need QECC- and architecture-aware optimization strategies and cost model

The 2nd Workshop on HPC/AI Integration with Quantum Computing / Networking (HAIQ2026)

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