

Synthesis on Atom Computation

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May 21, 2024

Quick Review of Atom Computation

- **Control Mechanisms:**

- Neutral atoms controlled by laser lattice (stationary)
- Laser tweezers (for movement)

- **Single Qubit Gate:**

- $U3 : (\Omega_T \cos \varphi, \Omega_T \sin \varphi, \delta T)$

- **Multi-Qubit Gate:**

- $CZ : 2|gg\rangle\langle gg| - I$

- 1. Decomposing and Routing Quantum Circuits Under Constraints for Neutral Atom Architectures**
2. Compiling Quantum Circuits for Dynamically Field-Programmable Neutral Atoms Array Processors
FPQA-C: A Compilation Framework for Field Programmable Qubit Array
3. Discussion

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- Decomposition Strategy
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Decomposition Strategy

- **Native Gate Set**

- Local CZ gates.
- Local $R_z(\lambda)$ gates.
- Global $GR(\theta, \phi)$ gates.

- **Euler-Angle Decomposition**

- Decompose any single-qubit gate $U3(\theta, \phi, \lambda)$ into Euler angles:

$$U3(\theta, \phi, \lambda) = R_z(\phi)R_y(\theta)R_z(\lambda)$$

Axial Decomposition

- **Decomposition of R_y Gate**

- Decompose $R_y(\theta)$ gate into global and local gates:

$$\prod_j R_{y_j}(\theta_j) = GR\left(-\frac{\pi}{2}, 0\right) \left[\prod_j R_{z_j}(\theta_j) \right] GR\left(\frac{\pi}{2}, 0\right)$$

- This involves a net global rotation of π .

Transverse Decomposition

- **Optimized Decomposition of R_y Gate**

- Decompose $R_y(\theta)$ gate using minimal global rotation angle:

$$R_y(\theta) = R_v\left(\pi, \frac{\theta}{2}\right) R_z(-\pi)$$

- Further decompose R_v gate into global and local gates:

$$R_v(\xi, \omega) = GR\left(\omega, \frac{\pi}{2}\right) R_z(\xi) GR\left(-\omega, \frac{\pi}{2}\right)$$

Addition step: Post-Processing and Optimizations

- **Axis of Rotation Adjustment**

- Change the axis of rotation of global gates to eliminate redundant R_z gates.

- **Gate Merging**

- Merge consecutive R_z gates to further reduce the gate count.

Comparison of Decomposition Methods

- **Axial vs. Transverse Decomposition**
 - Axial decomposition results in a net global rotation of π .
 - Transverse decomposition minimizes global rotation angle to $|\theta|$.
- **Advantages of Transverse Decomposition**
 - Up to 3.5x reduction in global gate pulse duration.
 - Up to 2.9x reduction in single-qubit gate execution time.

Summary

- Efficient decomposition of quantum circuits into native gate sets for neutral atom hardware.
- Transverse decomposition minimizes global rotation angles, leading to significant speedup.
- Post-processing optimizations further reduce gate count and improve execution time.

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Introduction to Atom Movement

- **Goal**

- Utilize physical atom movement to optimize routing in quantum circuits.
- Reduce overhead costs associated with traditional SWAP gate decompositions.

- **Challenges**

- Maintain atom fidelity and avoid interference.
- Optimize the movement paths to minimize execution time.

Atom Movement Constraints

- **Threshold Distance**

- When moving, an atom must stay at least d_{thr} away from any other atom to avoid interference.

- **Parallel Movement Constraints**

- Atoms with the same initial x -coordinate can move horizontally together only if they end up with the same final x -coordinate.
- Atoms with the same initial y -coordinate can move vertically together only if they end up with the same final y -coordinate.

- **Movement Speed**

- Atoms must be moved at speeds not exceeding $0.55 \mu\text{m}/\mu\text{s}$ to maintain qubit fidelity and entanglement.

Atom Array Configuration

- **Initial Mapping**

- Each program qubit is assigned to a unique hardware qubit to minimize routing operations.

- **Displacement**

- Atoms can be displaced from grid points by d_{thr} to facilitate SWAP operations without violating distance constraints.

- **Graph Definition**

- Nodes represent atom sites.
- Edges indicate direct movement paths between sites without violating d_{thr} .
- Edge weights represent the distance between atom sites.

Movement Costs and Optimization

- **Movement Costs**

- **Duration**

- Movement duration is the distance traveled divided by movement speed.

- **Errors**

- Atom movements incur idle errors but not gate errors.

- **Parallelism**

- Maximize parallel movements while adhering to constraints to optimize circuit duration.

- **Optimization Strategy**

- Use movement graph to determine the best paths for atom movement.
 - Adjust initial displacements to facilitate efficient SWAP operations.

Comparing SWAP-based and Movement-based Routing

- **SWAP-based Routing**

- SWAP gate decomposition results in high gate count and execution time.

- **Movement-based Routing**

- Atom movement reduces routing overhead and improves fidelity.
- Achieves up to 10x speedup and 2x improvement in fidelity.

Summary

- Utilize physical atom movement to optimize routing in neutral atom quantum computers.
- Maintain fidelity and avoid interference with strategic movement constraints and optimizations.
- Significant improvements in execution speed and circuit fidelity compared to traditional SWAP-based routing.

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- **Qubit Traps**

- Qubits are held in optical traps generated by Acousto-Optic Deflectors (AODs) and Spatial Light Modulators (SLMs).

- **Reconfigurability**

- AOD traps can move in rows and columns, allowing dynamic reconfiguration.
- AOD rows/columns cannot cross over or overlap during movement.

- **Entangling Gates**

- Entangling gates are applied using a Rydberg laser, effective when qubits are within a blockade range r_b .

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Overview of the Method

- **Goal**

- Develop a compiler for Dynamically Field-Programmable Qubit Arrays (DPQA).
- Optimize the placement and routing of qubits to minimize circuit depth.

- **Approach**

- Discretize the state space and formulate the problem as a Satisfiability Modulo Theories (SMT) problem.
- Use an SMT solver to find optimal solutions.

Discretization of State Space

- **Space Domain**

- Discretized into interaction sites to ensure qubits are either paired for gates or idle and well-separated.

- **Time Domain**

- Discretized into stages where qubit positions are adjusted and gates are executed.

SMT Model Constraints

- **Spatial Constraints**

- Qubits must be within the defined grid bounds:

$$0 \leq x_{i,s} < X, \quad 0 \leq y_{i,s} < Y \quad \forall i, s$$

- AOD rows/columns cannot cross each other.

- **Interaction Constraints**

- Qubits must be within r_b for entangling gates:

$$\text{dist}(q_i, q_j) \leq r_b$$

- No other qubit can be within $2.5r_b$ of a pair during a gate.

- **Temporal Constraints**

- Qubits in SLM traps remain stationary:

$$(a_{i,s} = 0) \Rightarrow (x_{i,s+1} = x_{i,s}) \wedge (y_{i,s+1} = y_{i,s})$$

Example of Compiled Quantum Circuit

- **Stages of Compilation**

- Load qubits into traps.
- Apply entangling gates at interaction sites.
- Move AOD rows/columns for next stage.

Hybrid Compilation Approach

- **Greedy Heuristic**
 - Iteratively maximize the number of gates executed per stage.
- **Optimal Approach**
 - Use SMT solver to find optimal solutions when problem size is small.

Summary

- Utilize reconfigurability and non-local connectivity of DPQA for efficient quantum circuit compilation.
- Formulate constraints as an SMT problem for optimal solutions.
- Implement hybrid approach for scalability.

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Compilation Framework

- **Qubit-Array Mapper**

- Uses MAX k-Cut on a gate frequency graph to minimize SWAP overhead.
- Coarse-grained mapping of qubits to arrays.

- **Qubit-Atom Mapper**

- Fine-grained mapping of qubits to specific atoms in the array.
- Load balance to prevent hardware constraint violations.

- **High-Parallelism Router**

- Iteratively identifies parallelizable 2Q gates.
- Decides atom movements and gate executions to maximize parallelism.

Qubit-Array Mapping Method

- **Gate Frequency Graph**

- Vertices represent qubits, edges represent gates.
- Edge weights determined by gate frequency.

- **MAX k-Cut**

- Finds mapping that maximizes inter-array 2Q gates.
- Greedy algorithm used for approximation.

Qubit-Atom Mapping Method

- **Load Balance Mapping**

- Ensures balanced distribution of qubits across rows and columns.
- Avoids constraint violations from dense qubit clusters.

- **Alignment Mapping**

- Maps qubit pairs with frequent 2Q gates to the same positions in different arrays.
- Enhances parallelism by aligning high-frequency gates.

High-Parallelism Router

- **Non-Dependent Frontier Gates**
 - Identifies and schedules gates with no dependencies.
- **Constraint Checks**
 - Ensures movements do not violate spatial or interaction constraints.
 - Greedily adds gates to the parallel set, checking each for legality.

- **Benchmarks**

- Diverse set of benchmarks including QASMBench, SupermarQ, Quantum Simulation, and QAOA circuits.

- **Metrics**

- 2Q gate count, circuit depth, and fidelity.
- Comparisons with IBM superconducting, FAA with long-range gates, and other topologies.

Unique Experimental Approach

- **Comprehensive Simulations**

- Evaluates logical error rates, execution times, and physical qubit requirements.
- Includes realistic modeling of movement overheads (heating, cooling, decoherence, atom loss).

- **Scalability and Performance**

- Demonstrates significant reductions in 2Q gate count and circuit depth.
- Achieves up to 1000x faster compilation speed compared to solver-based methods.

Summary

- FPQA-C effectively addresses qubit mapping, atom movement, and gate scheduling in FPQA.
- Incorporates innovative methods to handle hardware constraints and optimize performance.
- Experimental results highlight the advantages of FPQA-C over traditional approaches in terms of gate count, depth, and fidelity.

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