Synthesis on Atom Computation

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Quick Review of Atom Computation

- **Control Mechanisms:**
  - Neutral atoms controlled by laser lattice (stationary)
  - Laser tweezers (for movement)
- **Single Qubit Gate:**
  - $U3 : (\Omega\tau \cos\varphi, \Omega\tau \sin\varphi, \delta\tau)$
- **Multi-Qubit Gate:**
  - $C\mathcal{Z} : 2|gg\rangle\langle gg| - I$

Outline

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

Outline

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:

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

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.

Outline

1. Decomposing and Routing Quantum Circuits Under Constraints for Neutral Atom Architectures
    - Decomposition Strategy
    - Atom Movement Strategy

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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 μm/μs 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.

Movement Graph

- **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.

Outline

Setup (FPQA)

- Gateset:
  - Global CZ
  - Local $U3$
- Optical traps are configured in 2D arrays.
- Two-qubit entangling gates require qubits to be within a certain proximity without interfering with others.
- Constraints of physical movement of traps, ensuring each solution step complies with the DPQA constraints and remains executable.

Constraints in the Greedy Method

- **DPQA Architectural Constraints**:
  - Adhere to movement and interaction rules specific to DPQA.
  - Maintain the logical sequence of gate operations.
- **Minimum Gates Threshold ('M')**:
  - Strive to achieve at least 'M' gates per stage, where 'M' is dynamically adjusted based on solvability.
- **SMT Solver Integration**:
  - Use an SMT solver to find feasible solutions that maximize gate execution while respecting the constraints.

SMT Solver Role in the Greedy Method

- **Input**: Reduced and simplified problem instances as the complexity is peeled off.
- **Output**: Feasible configurations that allow the maximum number of gates ('M') to be executed per stage.
- **Dynamic Adjustment**: Modifies 'M' based on the ease or difficulty of finding a solution, optimizing the balance between speed and completeness of the solution.

Transition to Optimal Compilation

- **Criterion for Transition**: Shifts to the optimal SMT-based approach when a significant portion of the problem has been resolved or when only a small percentage of gates remains.
- **Rationale**: Ensures that the final solution is both efficient and adheres strictly to all operational constraints.

Conclusion

The integration of the SMT solver within the Greedy Method in this hybrid approach allows for a pragmatic reduction of quantum circuit complexity, setting the stage for a detailed and optimal final compilation using SMT.

Methods (FPQA)

- Qubit-Array Mapper:
  - K-cut problem aiming to maximize the summation of edge weights crossing different partitions
- Qubit-Atom Mapper:
  - SLM Array: Load balance mapping
  - AOD Array: Alignment AOD mapping
- High-Parallelism Router:
  - U3 gate
  - Check constraint

Outline

Discussion

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