Synthesis on Atom Computation

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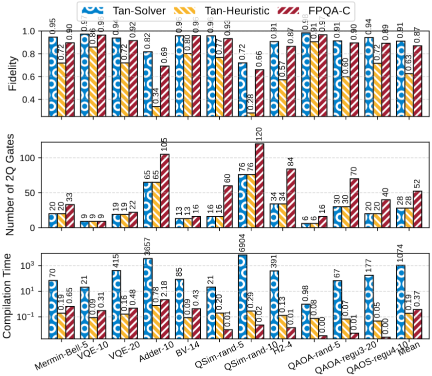
Outline

1. Compilation for Dynamically Field-Programmable Qubit Arrays with Efficient and Provably Near-Optimal Scheduling

Related Works

- ***Compiling Quantum Circuits for Dynamically Field-Programmable Neutral Atoms Array Processors***: Utilizes Z3 MST, but lacks scalability and fidelity considerations.
- ***FPQA-C: A Compilation Framework for Field Programmable Qubit Array***: Employs a rule-based algorithm, offering good scalability, but does not achieve the optimal count of 2Q gates.



Overview

- Background: Quantum computing with neutral atoms has advanced rapidly.
- Fidelity:

$$f = (f_1)^{g_1} \cdot \overbrace{(f_2)^{g_2} \cdot (f_{\text{exc}})^{|Q|S-2g_2}}^{\text{two-qubit gate}} \cdot \overbrace{(f_{\text{trans}})^{N_{\text{trans}}}}^{\text{atom transfer}} \cdot \overbrace{\prod_{q \in Q} (1 - T_q/T_2)}^{\textit{decoherence}}.$$

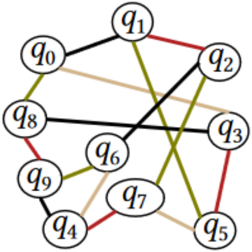
- Significant scalability: experiments with up to 6,100 qubits.
- The compilation process is broken down into three tasks: scheduling, placement, and routing.

Qubit Num	Gate Num	Scheduling	Placement	Routing	Codegen	Total
30	45	0.0008	137.32	0.0057	0.0184	137.35
60	60	0.0017	141.23	0.0124	0.0379	141.28
90	135	0.0023	144.43	0.0304	0.0630	144.52

Table: Timing Results for Different Qubit and Gate Numbers

Scheduling

- Scheduling is crucial for determining the sequence of operations. Graph edge coloring is used to model the scheduling problem.
- Each edge represents a two-qubit gate.
- Colors represent different stages.
- The goal is to minimize the number of stages while ensuring no two adjacent edges share the same color.



qubit interaction graph

stage	gate
0	g_3 g_6 g_7 g_{11}
1	g_0 g_5 g_9 g_{12}
2	g_2 g_4 g_8 g_{14}
3	g_1 g_{10} g_{13}

edge-color schedule

Scheduling: Graph Edge Coloring

Theorem

Vizing's Theorem: *For any simple graph G with maximum degree Δ, the chromatic index $\chi'(G)$ satisfies:*

$$\Delta \leq \chi'(G) \leq \Delta + 1$$

where $\chi'(G)$ is the minimum number of colors needed to color the edges of G.

- There exists an algorithm with runtime $O(|V| \cdot |E|)$ that provides an edge coloring $\phi : E \to \{0, 1, 2, \ldots, \Delta(G)\}$.
- The maximum gate count is $\binom{n}{2}$. Thus, the time complexity of scheduling is $O(n^3)$.

Placement

- Placement refers to assigning qubits to physical locations.
- Optimal placement minimizes the distance between interacting qubits.
- This reduces the need for long-distance routing, which can lower fidelity.

Formula

$$\sum_{g(q,q')\in G} w_g \cdot \mathrm{dist}(m(q), m(q'))$$

where w_g is the weight for gate g, m is the placement function from qubits to interaction sites, and dist is the **Euclidean distance**.

Placement Strategies

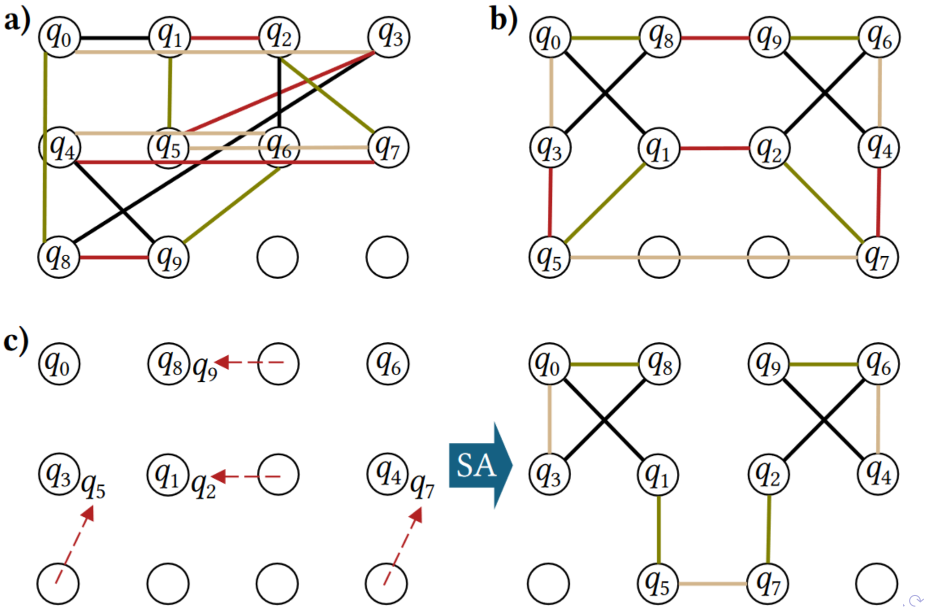
- Use of simulated annealing algorithms to find near-optimal solutions with a constant runtime.
- Balancing between computational efficiency and placement quality.

$$x \in \left[0, \max\left(\lfloor\sqrt{n}\rfloor + 4, x_{\max}\right)\right], y \in \left[0, \max\left(\lfloor\sqrt{n}\rfloor + 4, y_{\max}\right)\right]$$

Formula

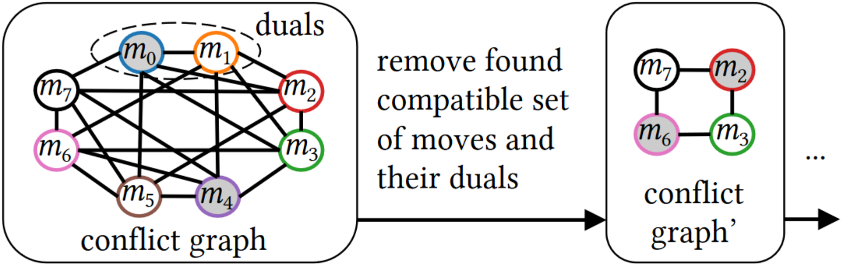
$$w_g = \begin{cases} 1, & \text{static placement} \\ \max\left(0.1, 1 - 0.1 s_g\right), & \text{dynamic placement} \end{cases}$$

Placement example



Routing

- Routing involves determining paths for qubits to move during computation. Ensuring minimal delay and avoiding congestion are key goals.
- A conflict graph represents the conflicts during the routing process.
- Nodes represent qubits movements, and edges represent conflicts.
- The problem is The Maximum Independent Set (MIS) problem, where one seeks to find the largest set of vertices in a graph such that no two vertices in the set are adjacent.



Greedy Algorithm for Bounded Degree Graphs

1). putting all vertices in a list (sorted by distance).

2). adding the first vertex to the IS.

3). removing all its neighbors from the list, and continuing 2-3.

Theorem

In bounded degree graphs, there are effective approximation algorithms with constant ratios. For example, a greedy algorithm that forms a maximal independent set by repeatedly choosing the vertex with the minimum degree and removing its neighbors achieves an approximation ratio of $(\Delta + 2)/3$ for graphs with maximum degree Δ. Approximation hardness bounds for these cases were shown by Berman and Karpinski (1999).

Routing Complexity

For the number of qubits n, the maximum number of gates is $n/2$, so the number of vertices is at most n ($|V| \leq n$):

- Checking conflicts for all pairs of vertices requires $O(|V|^2)$ time.
- Sorting the vertices requires $O(|V| \log |V|)$ time.
- The greedy algorithm requires $O(|V|^2)$ time. In the worst case, the greedy algorithm needs to be run $O(|V|)$ times.
- **In total, there can be $O(n)$ Rydberg stages, resulting in a routing time of $O(n^4)$.**

Only construct a graph on the first K vertices in the lists ($|V| = K$):

- **The windowed routing takse $O(n^2 \log n + n^2 K^2)$.**

Results and Comparison

- The compiler, Enola, shows significant improvements in performance.
- Achieves 3.7X stage reduction compared to existing works.
- Demonstrates 5.9X improvement in fidelity on benchmark sets.
- Highly scalable, capable of compiling circuits with up to 10,000 qubits within 30 minutes.
- Outperforms the current state of the art, OLSQ-DPQA.

Conclusion

- The compilation process for dynamically field-programmable qubit arrays involves scheduling, placement, and routing.
- The method provide near-optimal solutions for scheduling and efficient strategies for placement and routing.
- Enola compiler achieves significant improvements in stage reduction and fidelity.
- Future work includes further optimization and exploring additional constraints.
- Open source availability: `https://github.com/UCLA-VAST/Enola`