Increasing the Efficiency of Neutral Atoms by Reducing Qubit Waste from Measurement-related Ejections

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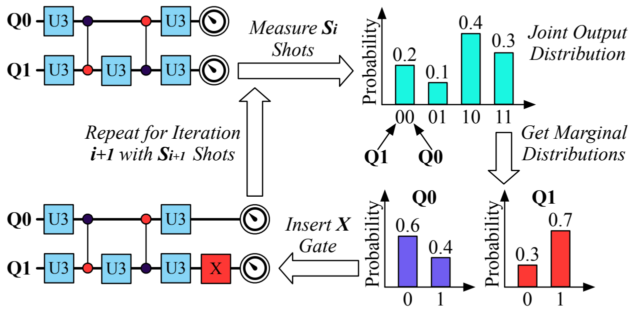

Figure 1: Overview of our proposed procedure.

Abstract

Quantum computing is an emerging field with the potential to accelerate computational tasks across various domains. As a complement to traditional high-performance computing, quantum computers promise exponential speedups for certain problems in areas such as cryptography, optimization, machine learning, and molecular simulation [2, 5]. Among quantum computing technologies, neutral atom systems offer several advantages, including customizable qubit topologies, lower decoherence rates, and improved scalability. These systems use arrays of individually trapped neutral atoms as qubits, with information encoded in their electronic states. However, neutral atom systems face a unique challenge in the measurement process, where atoms in the $|1\rangle$ state are physically ejected from the array. This leads to substantial time overhead in reloading the atom array between program executions, often exceeding the actual computation time by orders of magnitude.

To address this issue, we introduce a novel technique that significantly reduces the rate of qubit ejections in neutral atom systems during measurement. By minimizing ejections, our technique improves the performance of neutral atom computers. It leverages the probabilistic nature of quantum programs to predict which qubits are most likely to be in the $|1\rangle$ state just before measurement. It then strategically applies Pauli X gates to flip these qubits, reducing the probability of measuring them in the $|1\rangle$ state and thus avoiding ejection. After measurement, it reverts the states of the flipped qubits to obtain the true output values.

We evaluate several intervention scheduling techniques. Intervention scheduling refers to the strategy of determining how often to assess qubit states and apply X gates during the execution of a quantum program. The techniques evaluated include constant, proportional, linear, quadratic, and entropic intervals. Among these, the entropic interval technique shows the best performance. This method dynamically adjusts the frequency of interventions based on the rate of change in qubit state probabilities (what we call "entropy"). The frequency of interventions is thus adapted based on how rapidly the probability distributions change, allowing the technique to balance between refining its understanding of the qubit states and minimizing computational overhead.

In addition to reducing ejections, we maximize atom array utilization through strategic atom movements. Instead of reloading the entire array after each shot, we refill only the central region where the circuit is mapped, moving nearby atoms to fill vacancies. This approach significantly reduces the need for full array reloads, further improving system performance.

For evaluation, we use both random circuits and real quantum algorithms from the QASMBench suite. The random circuits, generated using Qiskit, have qubit sizes ranging from 16 to 30 and circuit depths of 4 to 15. These circuits represent a challenging use case, as they tend to have unstructured output states where qubits have close to 0.5 probability of being in either basis state. The real algorithms, comprising 12 different quantum computations with qubit counts ranging from 6 to 27, provide insight into the technique's performance on practical quantum tasks.

Our experiments are conducted on a simulated 256-atom array, mirroring the configuration of the QuEra Aquila system. Active qubits are mapped to the center of the atom array, surrounded by idle qubits. When atoms are ejected, they are replaced by nearby idle qubits, with a full array reload occurring only when insufficient idle qubits remain. This strategy significantly reduces the need for full array reloads, further improving system performance.

For random circuits, our technique achieves a median reduction of 25% in atom ejections, array reloads, and atom movements compared to baseline execution without mitigation. The impact is more pronounced for real quantum algorithms, where the median number of atom ejections is reduced by 53%, array reloads by 54%, and atom movements by 53%. This superior performance on real algorithms is attributed to their more structured output, where output states are usually more concentrated, making it easier for the technique to predict qubit states accurately. Importantly, performance with the best intervention technique (entropic) comes close to that of an oracle with perfect knowledge of qubit states, underperforming by only 1.35-1.40%.

Regarding related work, recent research has addressed measurement-related challenges in quantum computing, particularly for superconducting quantum computers [3, 4, 10, 12, 13]. However, these works don't relate to the unique architecture of neutral atom systems. Several works have focused on optimizing compilation of quantum circuits for neutral atom systems [1, 6–9, 11]. While these improve circuit execution, our work is the first to address reducing the amount of time spent on reloading the atom array between shots from a systems perspective.

By reducing the time spent on array reloads, our novel technique enables more efficient utilization of neutral atom quantum computers, accelerating progress in quantum algorithm development

and practical applications. As neutral atom systems continue to scale up in capability, contributions like the one presented here will play a crucial role in maximizing their performance and usability, paving the way for more efficient and scalable quantum computing technologies.

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