Optimization of Quantum Computer Throughput by Quantum Multi-Programming

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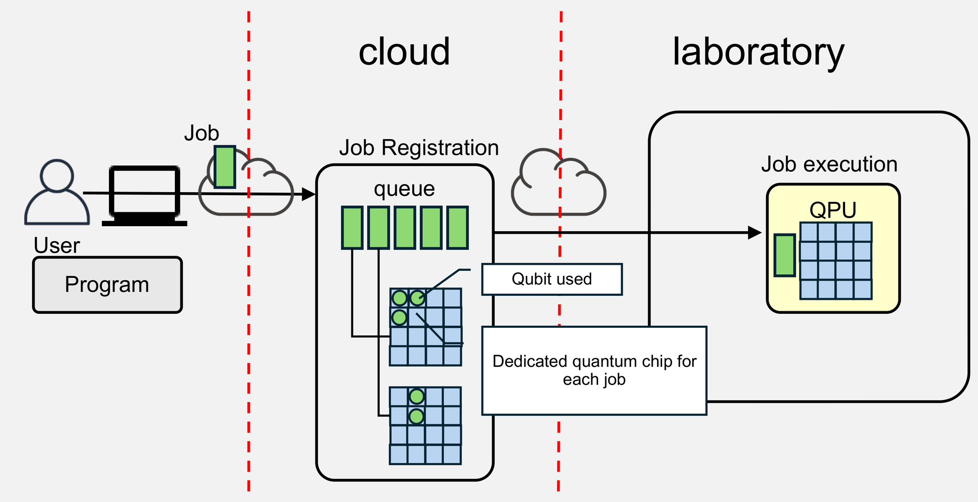
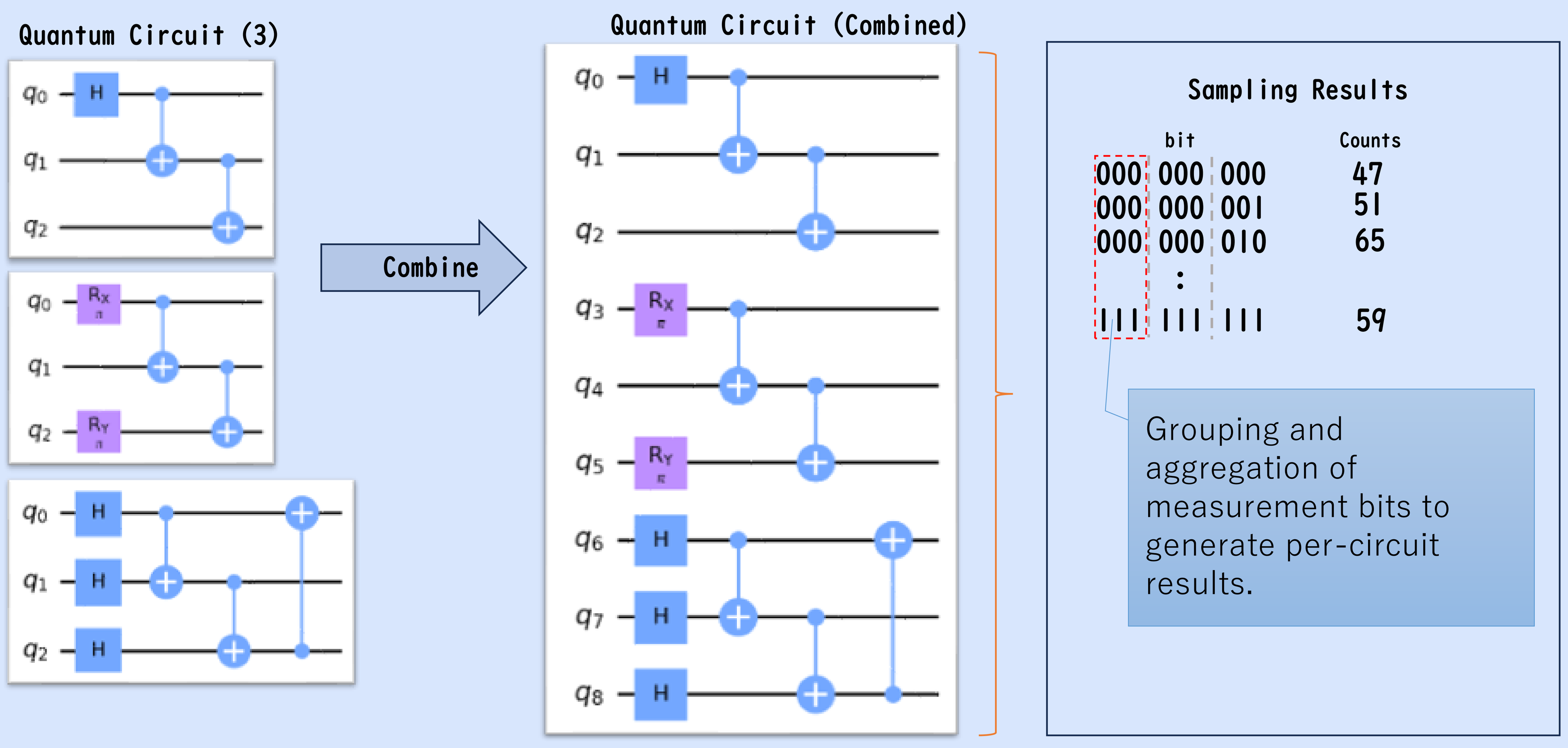
Abstract

While research into quantum computing has become increasingly active, usable hardware resources remain scarce. As the number of users grows, long job wait times have emerged as a significant bottleneck, hindering rapid experimentation and reducing overall research efficiency. To address this, maximizing the utility of limited resources is essential. In this poster, we propose a method called "Quantum Multi-Programming" to enhance system throughput by executing multiple quantum circuits in parallel. We model both the execution environment and the quantum circuits as graphs. The allocation of multiple circuit graphs onto the environment graph is then formulated and solved as a Constraint Satisfaction Problem (CSP). This approach aims to reduce wait times and improve the practical efficiency of quantum computing systems.



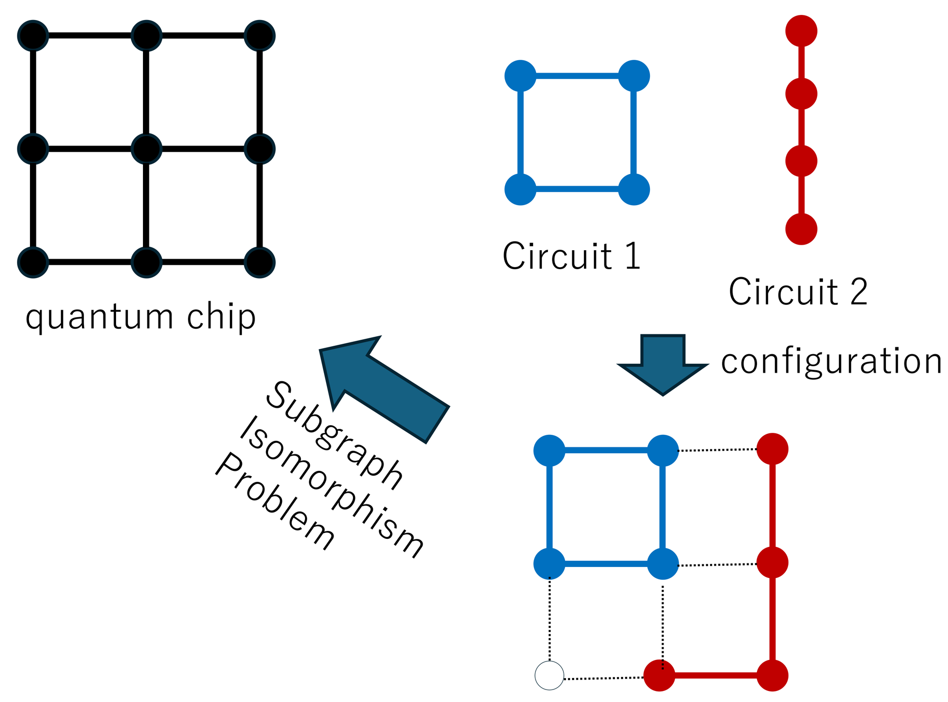
Quantum Multi-Programming

In this research, we propose to improve the throughput by executing multiple quantum circuits in parallel by "Quantum Multi-Programming" to reduce the latency [1], [2], [3]. Specifically, as shown in figure, a plurality of quantum circuits are combined and executed as one quantum circuit.



Subgraph Isomorphism Problem

"Quantum Multi-Programming" is achieved by modeling both the quantum chip and the quantum circuits as graphs, and then determining whether the graphs of multiple quantum circuits can be mapped onto the graph of the quantum chip. Specifically, if the graph representing the quantum circuits is subgraph isomorphic to the graph representing the quantum chip, it implies that a valid mapping exists. Although the Subgraph Isomorphism Problem is known to be NP-complete, small-scale instances can be solved efficiently using heuristic solvers. Therefore, we utilized OR-Tools[4] to solve this problem.



Methods

Pre-transpilation

Before mapping, we perform pre-transpilation on the quantum circuits. This step is necessary to align the circuits with the physical constraints of the hardware, specifically accounting for CNOT gate directions and the specific topology of the quantum chip.

Constraints for Allocation

We define the following constraints to formulate the mapping problem:

- Unique Mapping: Each node in the quantum circuit must be mapped to a distinct node on the quantum chip (injective mapping).
- Resource Availability: Nodes that have already been allocated cannot be reused.
- Connectivity Preservation: Every edge in the quantum circuit must correspond to an existing edge on the quantum chip graph.

Search & Iteration

We utilize a Constraint Satisfaction Problem (CSP) solver to search for a mapping that satisfies the above constraints. Once a valid mapping is found, the corresponding nodes are effectively removed from the available quantum chip graph (resource masking), and the process is repeated for subsequent circuits.

Results

As a result of this table, 200 quantum circuits could be summarized to 68.8 on average. In short, they showed that quantum multiprogramming can increase the throughput of quantum computers by 2.9 times. The throughput improvement rate is a value obtained by dividing [the number of quantum circuits before allocation] by [the number of quantum circuits after allocation]. The upper limit of the theoretical value is the upper limit when the CNOT direction and the circuit shape are ignored and the circuit size is added up to 64 qubits.

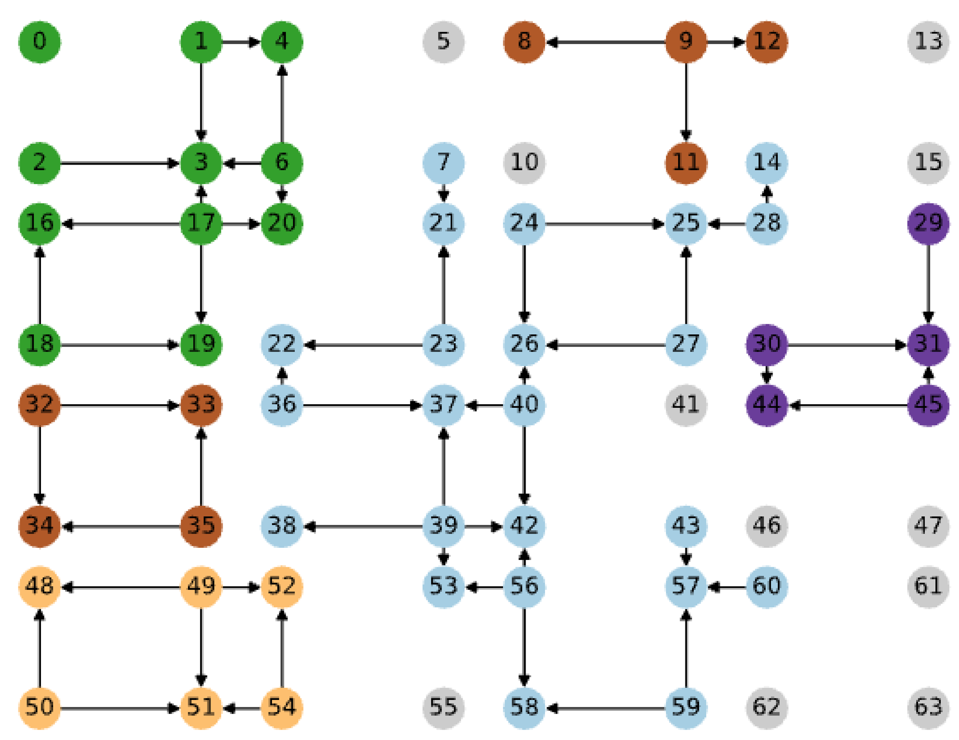
ALLOCATION RESULTS

Item	Result
Number of circuits after allocation (average)	68.8
Number of circuits after allocation (average of theoretical upper limit)	51
Processing time (average)	197.14 sec

Conclusions

Compared to the theoretical upper bound, it seems that there are still qubits to be filled, but as shown in figure, they are allocated.When the direction of the CNOT and the shape of the quantum circuit are taken into consideration, it is difficult to further allocate the available qubits.

Since unreasonable allocation would require SWAP and prevent efficient quantum computation, the current allocation is considered sufficient.



References

[1] X. Dou and L. Liu, "A new qubits mapping mechanism for multi-pro-gramming quantum computing," in Proceedings of the ACM International Conference on Parallel Architectures and Compilation Techniques, 2020, pp. 349–350.

[2] S. Niu and A. Todri-Sanial, "Enabling multi-programming mechanism for quantum computing in the NISQ era," Quantum, vol. 7, p. 925, 2023.

[3] G. Park, K. Zhang, K. Yu, and V. Korepin, "Quantum multi-programming for Grover's search," Quantum Information Processing, vol. 22, no. 1, p.54, 2023.

[4] OR-Tools: https://developers.google.com/optimization?hl=ja

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