FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
DDS Department of DATA SCIENCE

Fraunhofer IIS

Master thesis:

Optimized Qubit Routing for Commuting Gates

Topic description

Qubit routing by swap insertion is a subroutine in the process of compiling quantum algorithms onto specific hardware. Quantum algorithms are usually formulated in the circuit model of quantum computation. Such a circuit consists of wires representing qubits as well as gates representing operations applied to pairs of qubits. In the circuit model, gates may be applied on any pair of qubits. However, this is not the case in currently available quantum processors. Here, two-qubit gates can only be applied on specific pairs of qubits defined by the *hardware connectivity graph*. Now the task is to find a mapping of qubits in the quantum circuit to qubits in the hardware graph such that for each two-qubit gate the corresponding circuit qubits are located at neighboring hardware qubits. The example in Figs. 1a and 1b shows that this is not always possible directly.

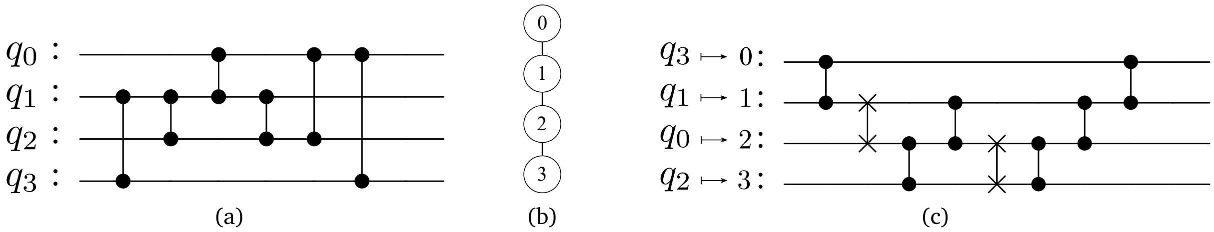

Figure 1: Example for a quantum circuit (a) consisting of four logical qubits (horizontal wires) as well as two-qubit gates (filled bullets with vertical lines). Although drawn here indistinguishable, two-qubit gates are different in general and the order matters. The circuit in (a) is not compatible with the hardware connectivity graph shown in (b). The routed circuit in (c) is equivalent to the quantum circuit in (a) and fulfills the hardware connectivity restrictions from (b). The initial mapping is shown on the left. Swap gates (crosses with vertical lines) change the mapping.

In such a case, it is necessary to insert additional *swap gates* into the algorithm. They effectively swap the positions of two circuit qubits in the hardware graph. The result is a circuit meeting the connectivity restrictions which is equivalent to the original one when taking into account the permutation resulting from initial mapping and swap gates. A simple example for this procedure is shown in Figure 1c. When solving the routing by swap insertion problem, a natural objective is to minimize the number of swap gates added.

Qubit routing is an NP-hard problem and exact approaches based on integer programming or satisfiability suffer from intractable runtimes [1, 2]. However, heuristics leave large room for improvement [3].

In general, the order of the two-qubit gates in the circuit matters. Some relevant applications, however, have blocks of commuting gates, i.e., sequences of gates in which the order is not relevant. Then, the order of gates is an additional degree of freedom which can be optimized in order to further reduce swap overhead. This has been exploited by several heuristic approaches [4, 5, 6].

The goal of this thesis is to develop, analyze, implement and evaluate an exact integer programming model for qubit routing with commuting gates.

Preknowledge in quantum computation is not required, however basic familiarity with discrete optimization is necessary.

This thesis will be supervised jointly by the the Department of Data Science (Frauke Liers) and the Fraunhofer IIS.

Contact

Friedrich Wagner

friedrich.wagner@iis.fraunhofer.de

In case of interest please send an email including a Transcript of Records, a short Letter of Motivation as well as a preferred starting date.

References

[1] Giacomo Nannicini, Lev S. Bishop, Oktay Günlük, and Petar Jurcevic. Optimal qubit assignment and routing via integer programming. *ACM Transactions on Quantum Computing*, 4(1), oct 2022.

[2] Robert Wille, Lukas Burgholzer, and Alwin Zulehner. Mapping quantum circuits to ibm qx architectures using the minimal number of swap and h operations. In *Proceedings of the 56th Annual Design Automation Conference 2019*, DAC '19. ACM, June 2019.

[3] Friedrich Wagner, Andreas Bärmann, Frauke Liers, and Markus Weissenbäck. Improving quantum computation by optimized qubit routing. *Journal of Optimization Theory and Applications*, 197(3):1161–1194, may 2023.

[4] Mahabubul Alam, Abdullah Ash-Saki, and Swaroop Ghosh. Circuit compilation methodologies for quantum approximate optimization algorithm. In *2020 53rd Annual IEEE/ACM International Symposium on Microarchitecture (MICRO)*, pages 215–228, 2020.

[5] Lingling Lao and Dan E. Browne. 2qan: A quantum compiler for 2-local qubit hamiltonian simulation algorithms. In *Proceedings of the 49th Annual International Symposium on Computer Architecture*, ISCA '22, page 351–365, New York, NY, USA, 2022. Association for Computing Machinery.

[6] Atsushi Matsuo, Shigeru Yamashita, and Daniel J. Egger. A SAT approach to the initial mapping problem in SWAP gate insertion for commuting gates. *IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences*, 2023.