

AQuCiDe: Architecture Aware Quantum Circuit Decomposition

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We have been witnessing very fast developments in quantum computing over the last decade, with several demonstrable physical realizations being reported (viz. by IBM, Microsoft, Google, Intel, DWave and many others). Various implementation technologies are being explored for realizing quantum computers, each having its specific quantum gate library and architecture. Motivated by this, researchers have worked on the design, synthesis, and mapping of algorithms to quantum computers. Typically a given function is first synthesized using reversible gates, which are then decomposed using some low-level quantum gate library and thereafter mapped to a specific quantum architecture. One of the most commonly used library is the Clifford+T library, which is known to be universal and also fault-tolerant.

There exists several works to decompose Multiple Control Toffoli (MCT) gates into quantum gates from the Clifford+T library. The library consists of Hadamard (H), NOT (X), controlled-NOT (CNOT) and phase shift (T) gates. Some of the earlier methods ([1]) have used methods like elimination of superposition, moving to diagonal or removing phase shifts along the columns, etc. to transform a matrix into identity matrix. However, these methods impact all the columns rather than a particular one. The approach used in [2] considers the matrix only once that does not affect any other columns.

Today's quantum computers are built with different architectures and hence architecture aware decomposition of MCT gates are important. None of the existing methods have considered architecture-aware decomposition of MCT gates. Current physical quantum machines have various architectural constraints [3], [4] that limit the way the qubits can interact among themselves. We propose a decomposition algorithm that takes the physical qubit architecture as an input, and creates a quantum circuit comprising of gates from the Clifford+T library. In this work clean and dirty ancilla qubits have been considered for the decomposition. The proposed architecture aware decomposition approach works in the following way:

(i) Initially for each MCT gate, we obtain the corresponding interaction graph. For a 2-controlled MCT gate, the realization using Clifford+T netlist varies depending on the available ancilla and depth of T gate [5]. Fig. 1 shows a Toffoli gate,

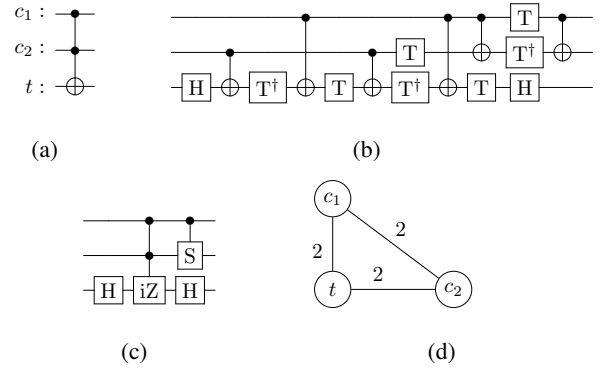


Fig. 1: (a) Toffoli gate, (b) Clifford+T realization, (c) Realization using 2-controlled iZ and 1-controlled S gates, (d) Interaction graph.

its equivalent realization and corresponding interaction graph.

MCT gate with more than 2-control inputs often requires ancilla qubits to decompose it in terms of 1- and 2-qubit gates. For performing such decomposition two possibilities exist: (a) The number of gates can be minimized by using 2-controlled $\pm iZ$ gates in intermediate stages of decomposition as shown in Figs. 2a and 2c. (b) However, there are some cases where 2-controlled $\pm iZ$ gate cannot be used. For the netlist shown in Fig. 2b, the controlled- S gate and its inverse gate cannot be removed completely due to the presence of a CNOT target between them. The interaction graph shown in Fig. 2d corresponds to the decomposed netlist after removing only a CNOT pair from the controlled- S/S^\dagger pair.

Fig. 3 shows the realization of a 4-controlled MCT gate using two dirty and clean ancilla qubits. The interaction graph of the decomposed netlists using dirty and clean ancillas are shown in Figs. 4a and 4b respectively. For clean ancillas, the interaction graph of decomposed MCT gate netlist have less number of edges and smaller edge weights compared to the interaction graph for dirty ancillas. The number of edges and edge weights remains uniform as number of controls qubits of MCT gate as well as use of ancilla qubits increases. Fig. 4c and 4d show the generalized interaction graph of an n -controlled MCT gate when decomposed using $n-2$ ancillas of type dirty and clean respectively.

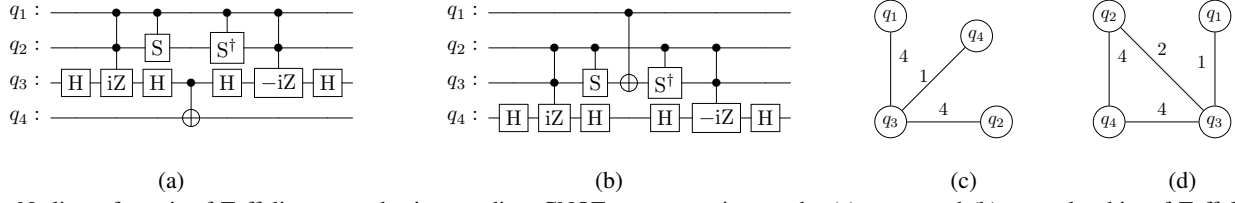


Fig. 2: Netlists of a pair of Toffoli gates and a intermediate CNOT gate operating on the (a) target and (b) control qubits of Toffoli gates, and their corresponding interaction graphs (c) and (d), respectively.

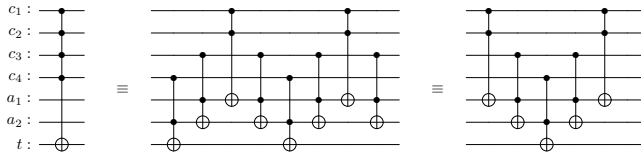


Fig. 3: Decomposition of a 4-controlled MCT gate as a sequence of 8 and 5 Toffoli gates using 2 dirty and clean ancilla qubits respectively.

(ii) For a given reversible netlist, the interaction graph of each decomposed MCT gate can be obtained as above. Fig. 5 shows the interaction graph of a reversible netlist decomposed using clean ancilla qubits.

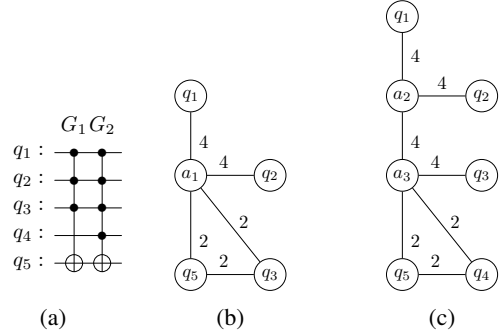


Fig. 5: A reversible circuit comprising 2 MCT gates and their corresponding interaction graphs of decomposed networks that are obtained using clean ancilla qubits a_1 , a_2 , and a_3 .

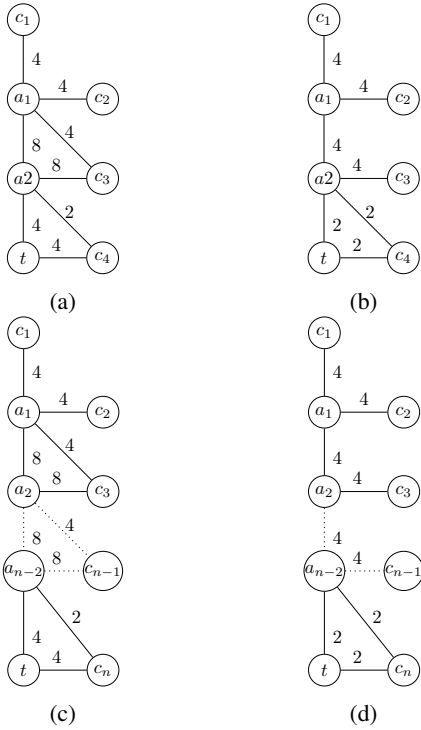


Fig. 4: Interaction graph of a 4-controlled and a n -controlled MCT gate decomposed using 2 (a) dirty / (b) clean and $n - 2$ (c) dirty / (d) clean ancilla qubits.

(iii) For a given qubit architecture all the interaction graphs are mapped and merged in sequence. For example, the interaction graph (see Fig. 5c) of the 2^{nd} reversible gate from the netlist shown in Fig. 5a, can be mapped on a 20-qubit hexagonal layout as shown in Fig. 6 with corresponding qubit

selection and edge highlighted.

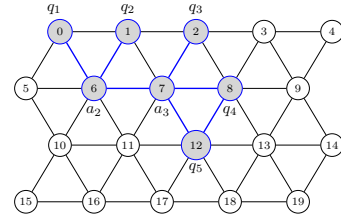


Fig. 6: A possible mapping on a Hexagonal qubit coupling layout.

The proposed decomposition approach is suitable for mapping the logical qubits of a given decomposed netlist to any given physical qubit architecture. The decomposition of MCT gates can be carried out both using dirty ancilla as well as clean ancilla qubits for better optimization. In the final version of the paper, experimental results for both IBM QX as well as hexagonal target architectures shall be provided. To the best of knowledge of the authors, this is the first attempt towards architecture aware decomposition of reversible gate netlists with respect to a target quantum gate library.

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