Distributing Circuits Over Heterogeneous, Modular Quantum Computing Network Architectures

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Summary

We consider a heterogeneous network of quantum computing capable modules, sparsely connected by Bell states used to implement non-local gates. We introduce several techniques for transforming a quantum circuit into one implementable on an architecture of the aforementioned type, minimising the Bell states required.

Modular Quantum Computing

A network comprises a collection of quantum computing *modules*, and:

- Local Operations and Classical Communication.
- A quantum communication channel generating and consuming a Bell state, referred to as an *e-bit*, shared between two modules.

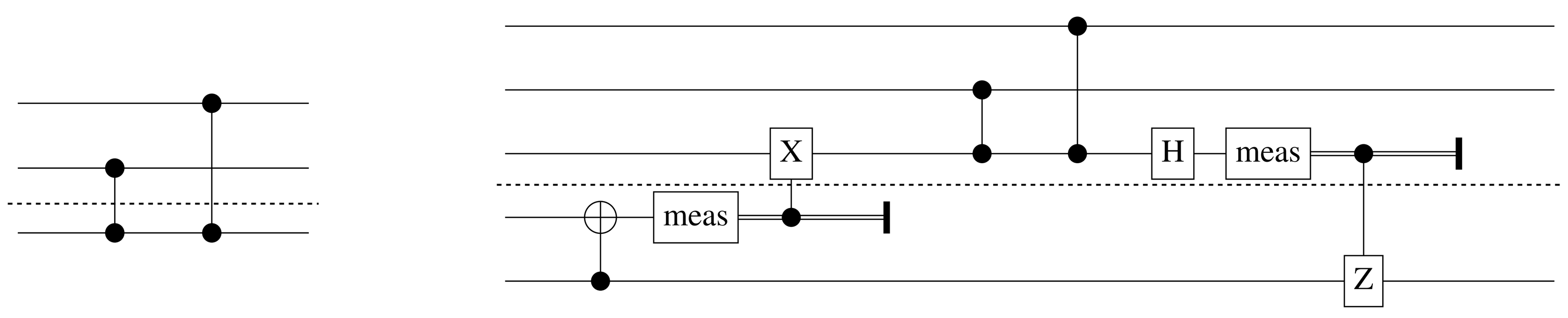


Figure 1. The EJPP protocol [1] simultaneously implements non-local CR_Z gates using one e-bit.

A distribution of a given circuit must consider:

Architecture: A distribution of a circuit implements an equivalent unitary, but respects restrictions on module sizes and inter-module connectivity.

E-bit Consumption: Compared to monolithic computation, the extra cost of distribution is the number of e-bits consumed, which should be minimised.

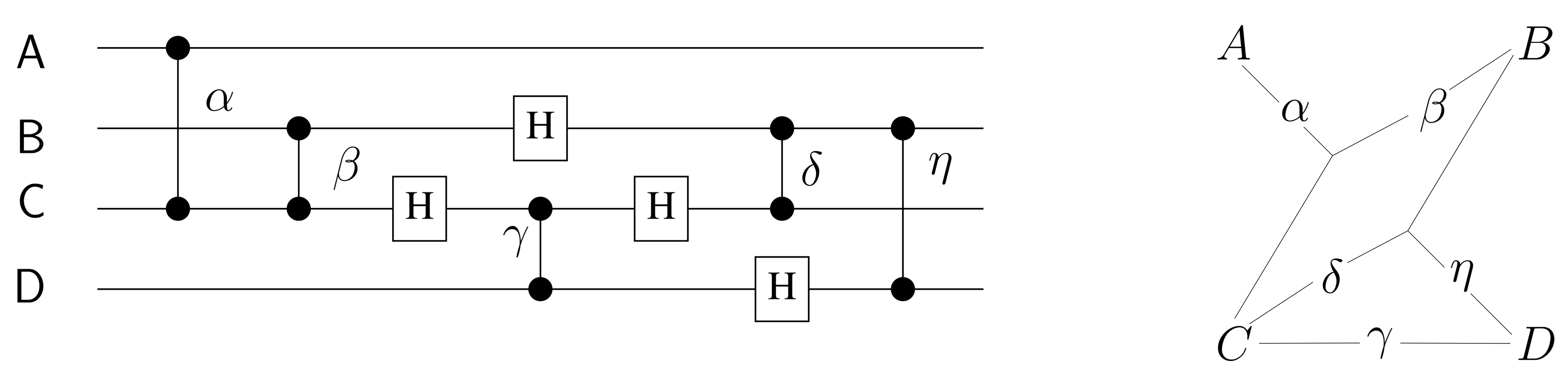
Distributing Quantum Circuits

Distributing a quantum circuit (DQC) can be divided into two subproblems:

Qubit allocation: Provide an allocation of each qubit of the circuit to a module. The number of qubits allocated to a module must not exceed its capacity.

Non-local gate distribution: Some gates, called *non-local* gates, then act on qubits in different modules. As in Fig. 1 we use simultaneous gate teleportation. We must decide how to group gates, and on which modules to enact them.

Qubit allocation and non-local gate implementation can both be solved simultaneously on homogeneous networks via a reduction to hypergraph partitioning [2].



(a) Circuit (b) Hypergraph

Non-local gates correspond to a hyperedge being cut by the partition. Minimising the number of cuts reduces the number of e-bits required for the distribution.

As a further means to reduce e-bit cost, embedding allows two CR_Z gates to be distributed via the same e-bit even when there are H gates between them.

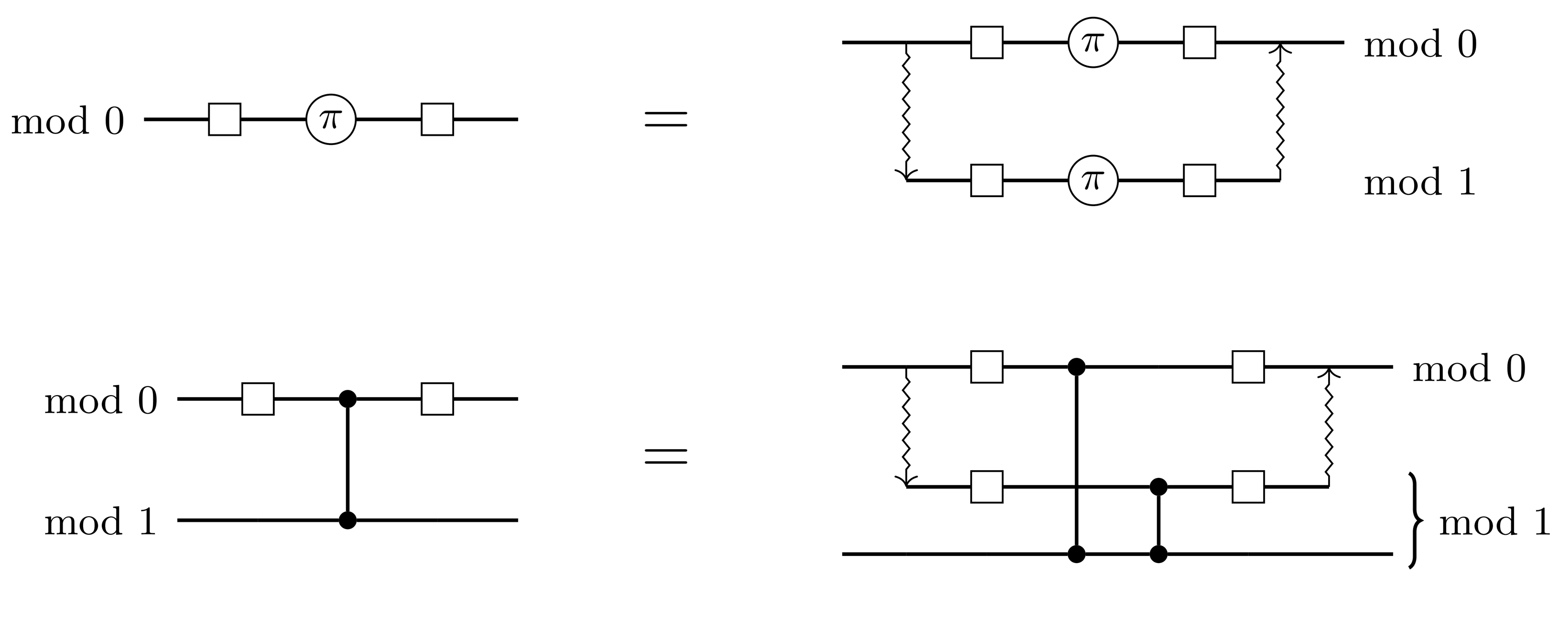


Figure 3. Embedding CZ and R_Z gates when distributing between modules.

Consider visiting poster 791, *Entanglement-efficient bipartite-distributed quantum computing with entanglement-assisted packing processes*, for details on embedding.

DQC on Heterogeneous Networks

We extend techniques from homogeneous to heterogeneous networks:

Partitioning on heterogeneous networks: In the case of heterogeneous networks, the cost function of a partition is updated to consider the distance between modules. Qubit and gate allocation techniques are introduced, based on simulated annealing (Annealing below) and greedy refinement (Partitioner).

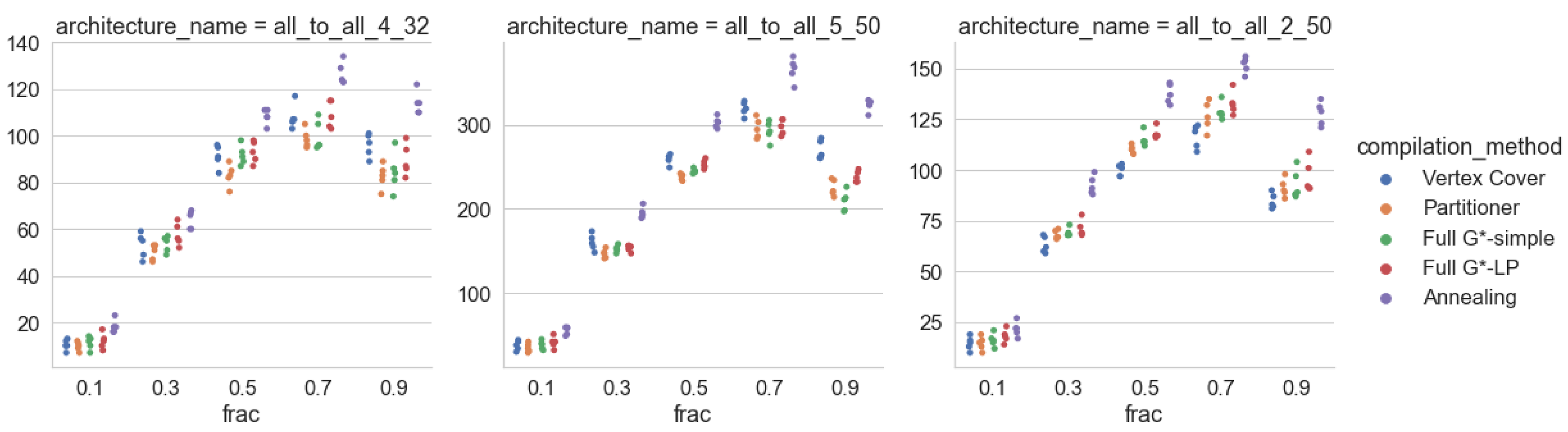
Steiner trees for entanglement distribution: Naively one would use entanglement swapping, and as many ebits as the length of the shortest path between modules, to connect them by a bell state. We can do better if we reuse the intermediate qubits to create Steiner trees connecting multiple modules.

Combine Steiner trees and embedding: A naive combination of embedding with Steiner trees results in non-local correction gates. We present an algorithm to appropriately disentangle parts of the Steiner tree to prevent such corrections.

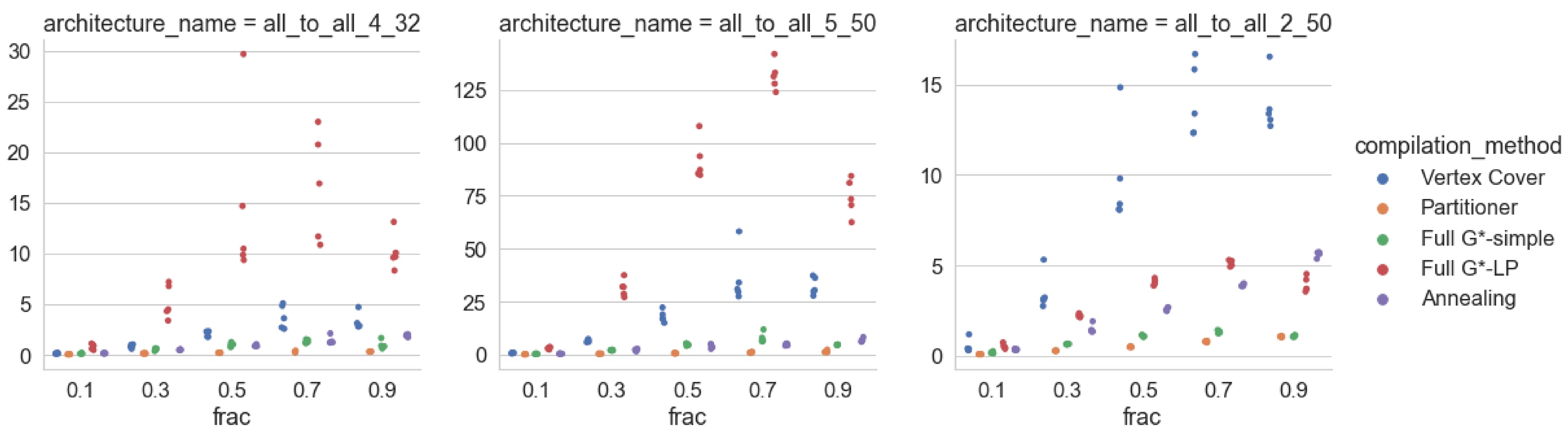
Greedy Refinement: Annealing and Partitioner specialise to the use of Steiner trees. Vertex Cover, derived from poster 791, specialises to use embedding. We present greedy refiners to improve the use of Steiner trees or embedding.

Results

Compare our techniques and [3]. Use homogeneous networks `all_to_all_m_n` with n qubits and m modules, and circuits with a varying fraction of CZ gates.



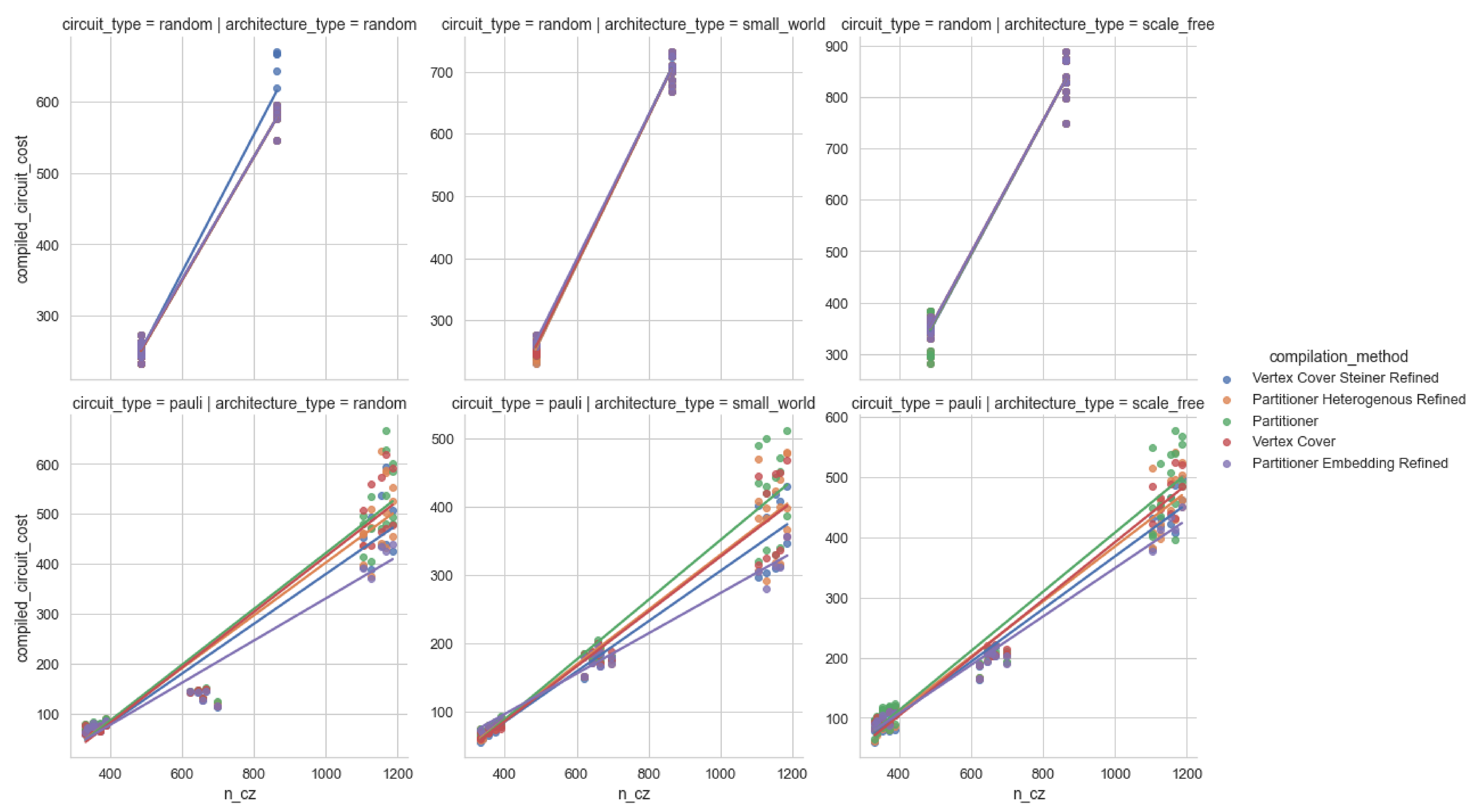
(a) E-bit cost.



(b) Time to distribute.

Vertex Cover is best on bipartite networks. Partitioner performs well and quickly.

Consider the heterogeneous case. Use Random circuits, similar to quantum volume circuits, and Pauli-Gadget circuits, constructed from circuit primitives common in VQE ansatze. We consider Random, Small-World, and Scale-Free networks.



Performance similar on Random circuits as opportunity for simultaneous gate teleportation is limited. Difference noticeable on Pauli-Gadget circuits where opportunity for simultaneous gate teleportation is greater. Partition refined to improve embedding performs best of all. Greedy refinement consistently results in improvement.

[1] J. Eisert, K. Jacobs, P. Papadopoulos, and M. B. Plenio. Optimal local implementation of nonlocal quantum gates.
[2] Pablo Andrés-Martínez and Chris Heunen. Automated distribution of quantum circuits via hypergraph partitioning.
[3] Ranjani G Sundaram, Himanshu Gupta, and CR Ramakrishnan. Efficient distribution of quantum circuits.