DISTRIBUTED QUANTUM ALGORITHMS: PDE AND MIS PROBLEMS



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Distributed Quantum Algorithms: PDE and MIS problems

Overview

- Intro to Distributed Quantum Computing
  - Distributed Quantum Architecture
  - Protocols for non-local operations
- Applications:
  - Distributed Quantum Variational PDEs Solver
  - Distributed Quantum Algorithm for MIS on neutral atoms QPU

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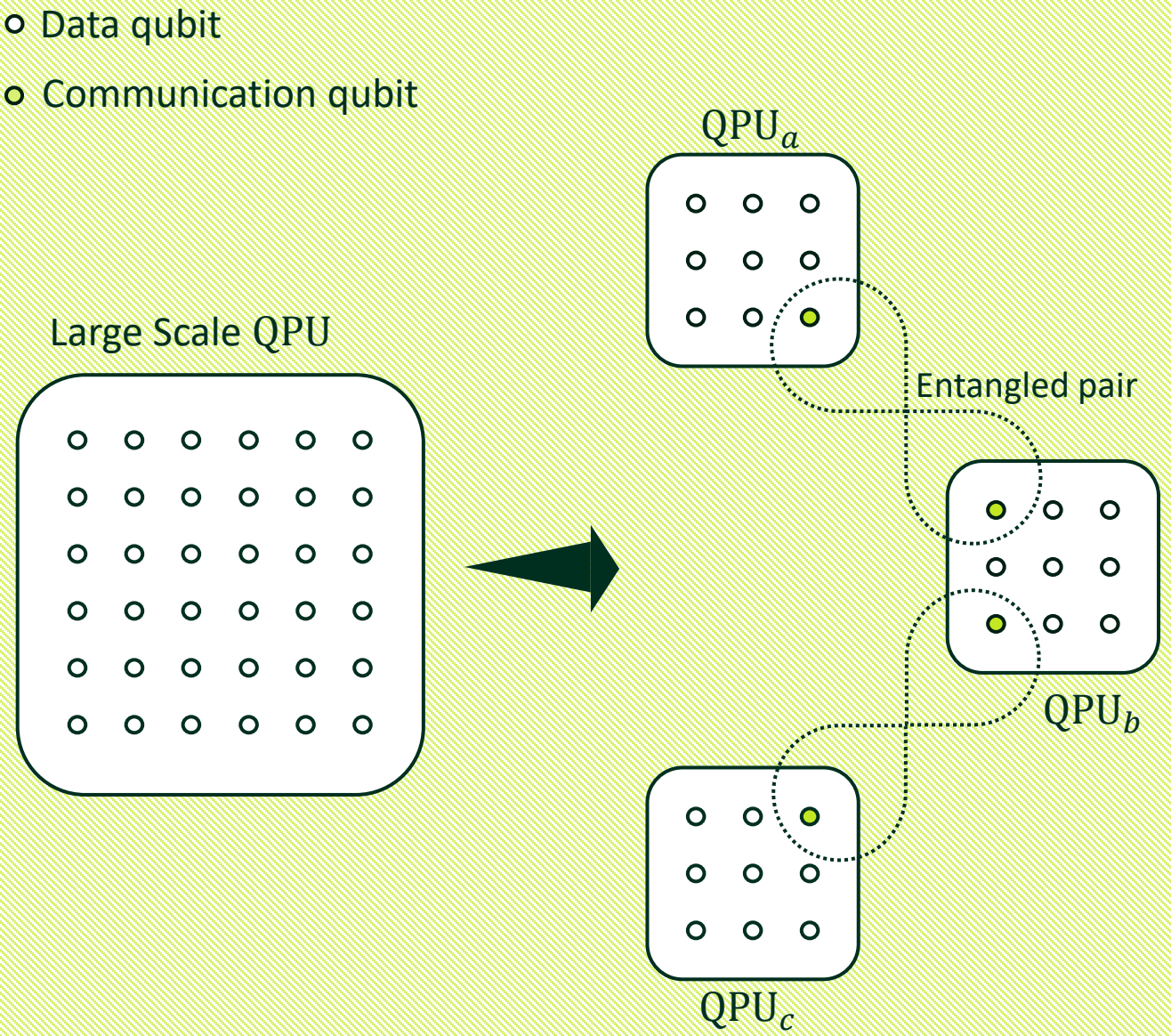
DISTRIBUTED QUANTUM ARCHITECTURE

Objectives

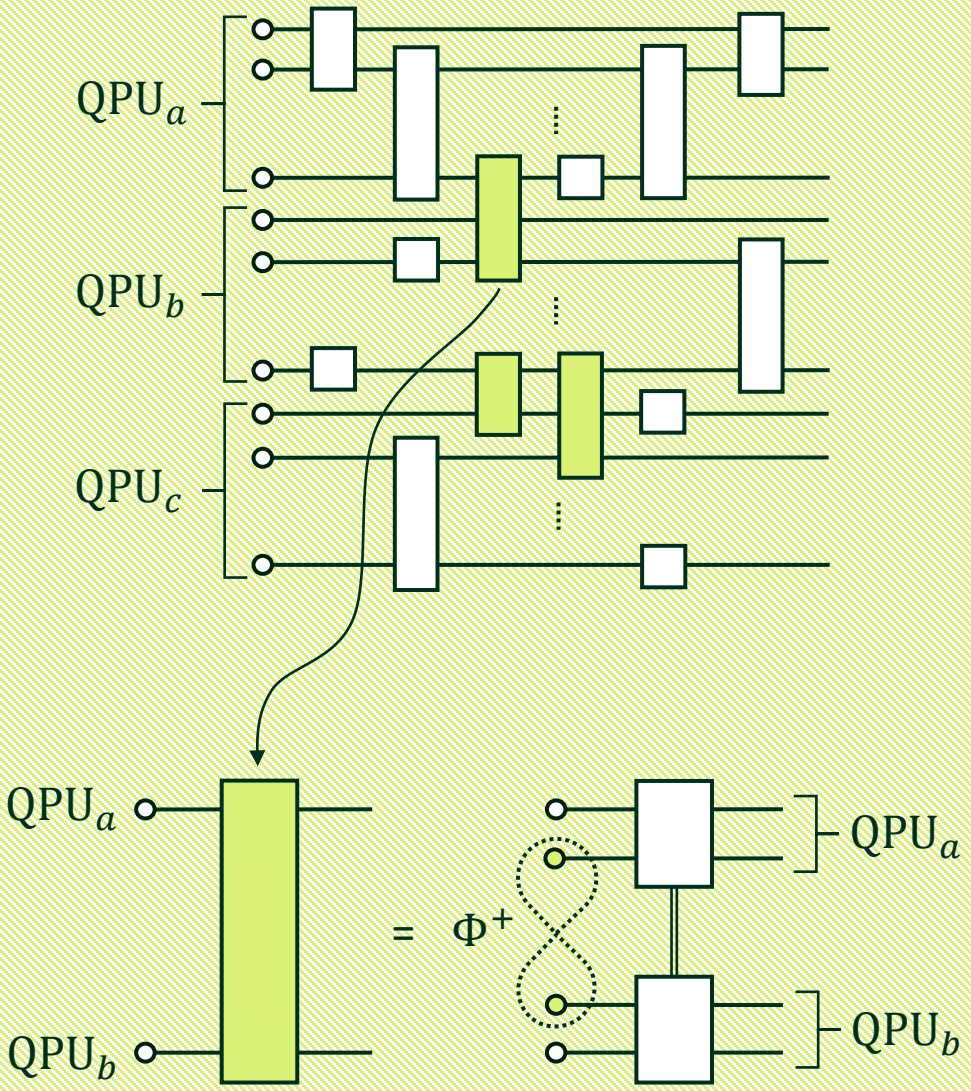
- **Scalability**
- **Fault tolerance**

Use a **network of QPUs** inter-connected with **classical** and **quantum connections** [1]

Individual **QPUs work together** to solve computational tasks **exceeding** the computational **resources available within a single device**



[1] Caleffi, M. & Amoretti, M. & Ferrari, D. et al. (2024). *Distributed quantum computing: A survey*. *Computer Networks*.



DISTRIBUTED QUANTUM COMPUTING

Assign each **data qubit** to a **QPU**

How to implement **non-local gates**?

Leverage **protocols** that utilize

- **Local quantum operations**
- **Classical communication**
- **Pre-distributed entanglement**, such as Bell pairs

$$|\Phi^+\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

Objective: **Minimize** the number of **non-local operations** and hence entanglement consumption

Gate teleportation protocol (TeleGate)

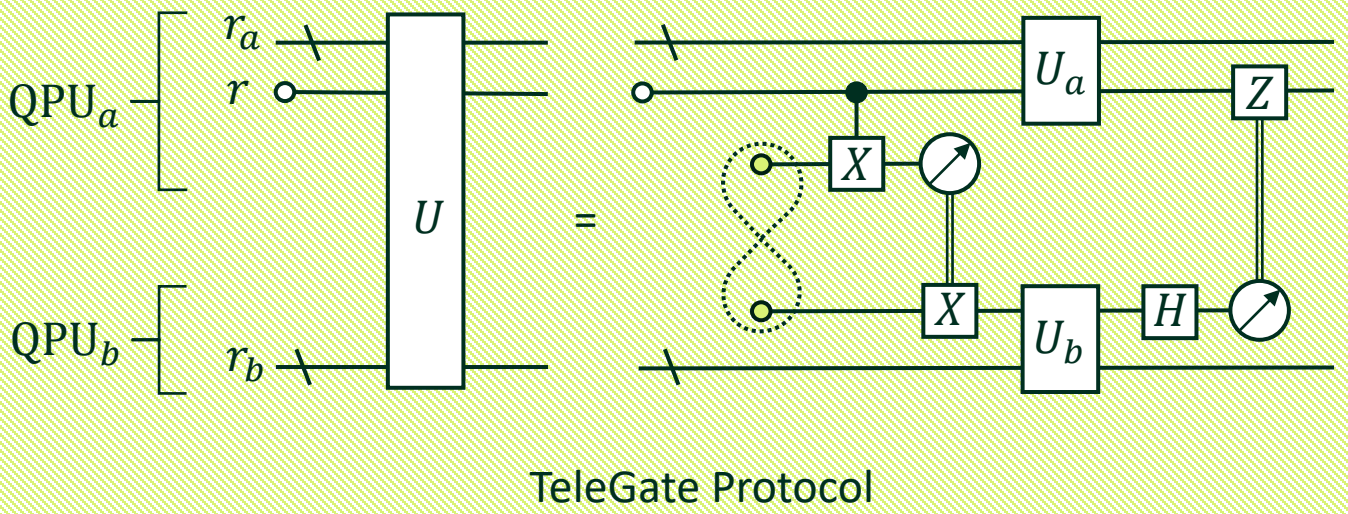
Gate sequences that can be **grouped into Packets** P of the form

$$P = \sum_{\substack{n=0 \\ \ell=0}}^{1} \Delta_{\ell n} |\ell\rangle\langle n|_r \otimes A_\ell \otimes B_\ell$$

can be **performed non-locally via TeleGate** [2]

Where:

- A_ℓ operates on r_a and B_ℓ on r_b
- $\Delta_{\ell n} = \delta_n^\ell$ or $\delta_n^{1-\ell}$



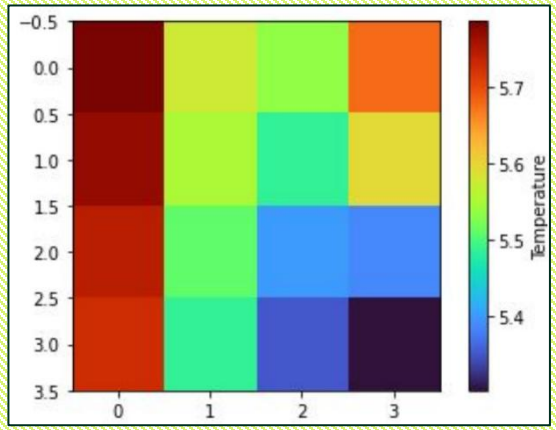
TeleGate Protocol

[2] Mengoni, R. & Nadalin, W. & Rotureau, J. & Lavdas I. et al. (2025). *Efficient Gate Reordering for Distributed Quantum Compiling in Data Centers*. *arXiv*.

Distributed Quantum Algorithm for Variational PDEs Solver

The resolution of **partial differential equations (PDEs)** has applications in virtually all fields of science. Here we focused on **heat diffusion in materials**.

In a stationary regime, we can place the problem in a **discrete form, using a mesh and finite elements methods.**

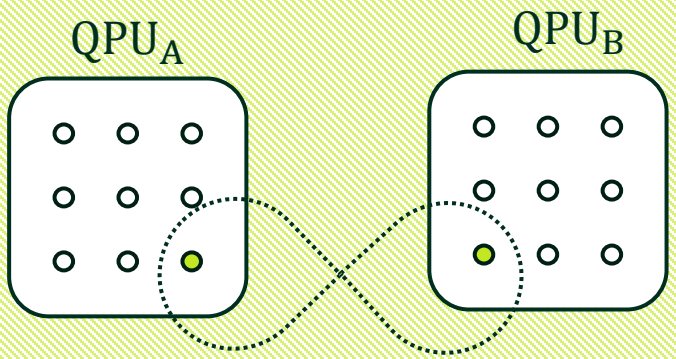


Variational Quantum Algorithm (VQA) is the standard approach to solve PDEs where the **solution vector $|x\rangle$ is approximated** on a quantum computer using a **parameterized state $|\psi(\boldsymbol{\theta})\rangle$** which optimizes the **cost function**

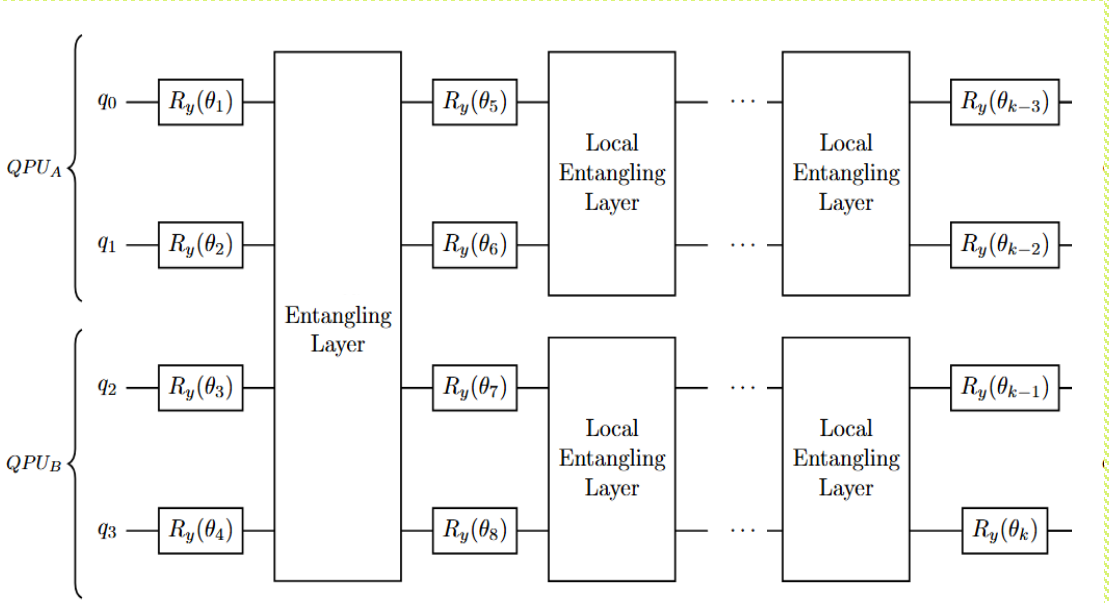
$$K|x\rangle = |f\rangle, \quad C = -\frac{|\langle f|\psi(\theta)\rangle|^2}{\langle\psi(\theta)|K|\psi(\theta)\rangle}$$

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Contributors: Welinq Algorithm Group, Kyrylo Kazymyrenko (EDF), Samuel Donachie (EDF)



Entangled pair



DQC Ansatz

Distributed Quantum Algorithm for Variational PDEs Solver

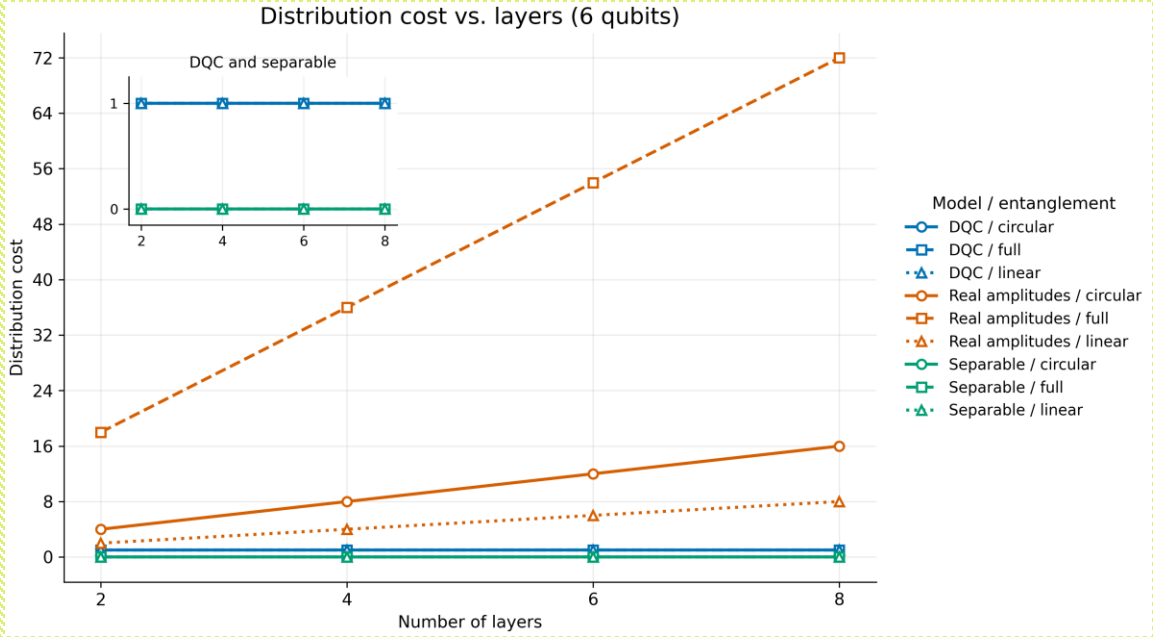
Previous works based on a single monolithic algorithm. Here **assumed a network of two interconnected QPUs** with **limited number of quantum links** connecting them

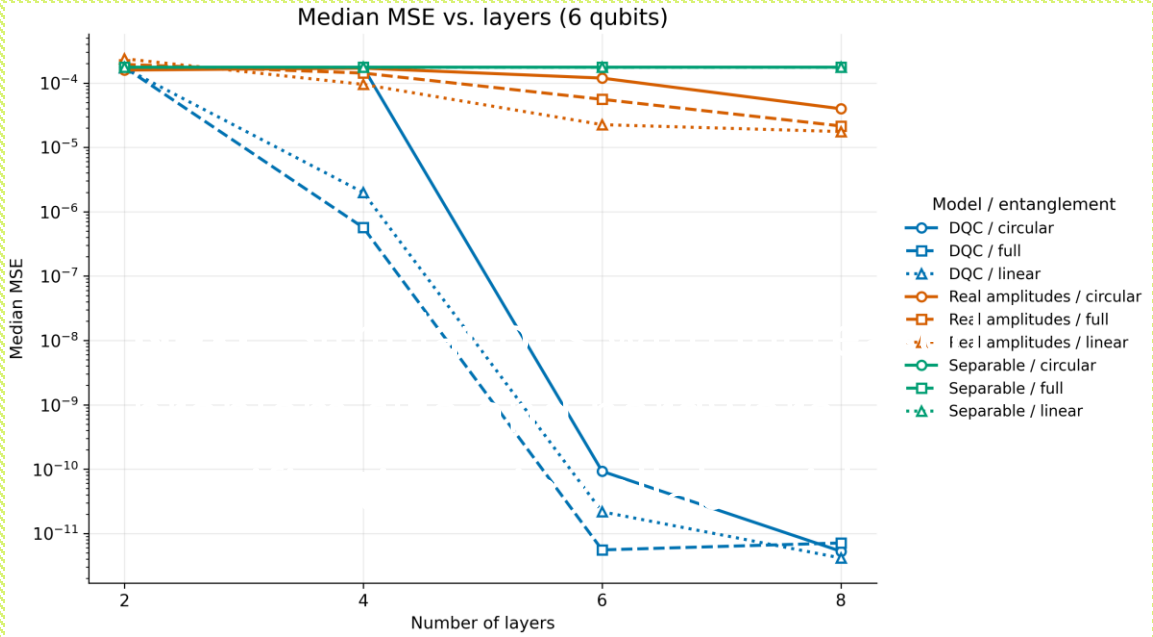
Objective: find a **natively Distributed Quantum Algorithm** able to **minimize the distribution cost** while also **accurately solving the PDEs,** and **compare it with the state of art quantum algo** used in PDE solvers

Distributed Quantum Algorithm for Variational PDEs Solver

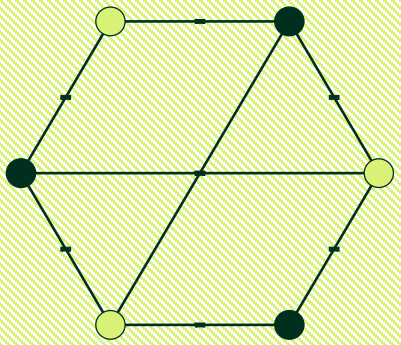
Proposed distributed quantum algorithm:

- **Lower distribution cost** than the RealAmplitude ansatz, only **one TeleGate necessary** for the **DQC ansatz**
- **Better solution quality in MSE** with respect to exact solution, compared to RealAmplitude and Separable ansatz
- Currently **investigating** effect of **Quandela hardware specifications** on **Telegate**





Smart Charging		Graph
Charge request by EV	↔	Vertex v_i
Conflict between charge requests	↔	Edge $(v_i v_j)$
Max nr. of EVS that can charge the same time	↔	MIS



$$G(V, E)$$

$$I \subseteq V\colon \forall u, v \in I, \{u, v\} \notin E$$

$$I^* = \max |I|$$

Distributed Quantum Algorithm for MIS on neutral atoms QPU

Smart Charging

Allocate charging requests of EVs so that conflicting requests are avoided

↓

Maximum Independent Set (MIS) Problem

MIS problems can be cast as binary optimization problem and solved using Adiabatic evolution algorithms on a single neutral atom QPU

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Contributors: Welinq Algorithm Group, Pascale Bendotti (EDF), Alexandra Sheremet (Pasqal/Welinq), Christoph Durr (Lip6-SU)

Distributed Quantum Algorithm for MIS on neutral atoms QPU

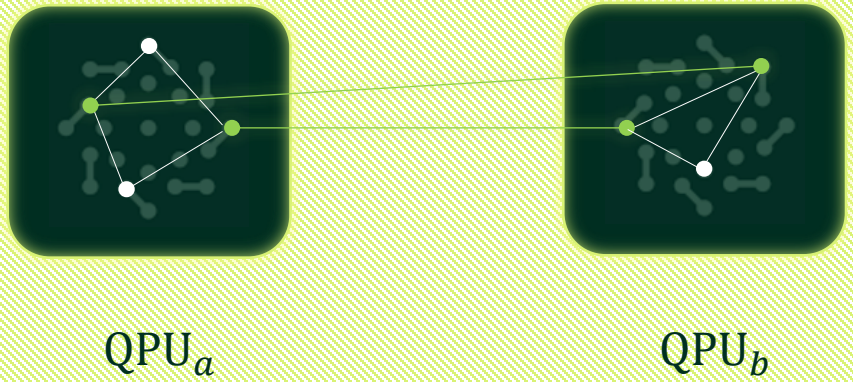
Here we assumed a **network of two interconnected neutral atom QPUs** with limited number of quantum links connecting them

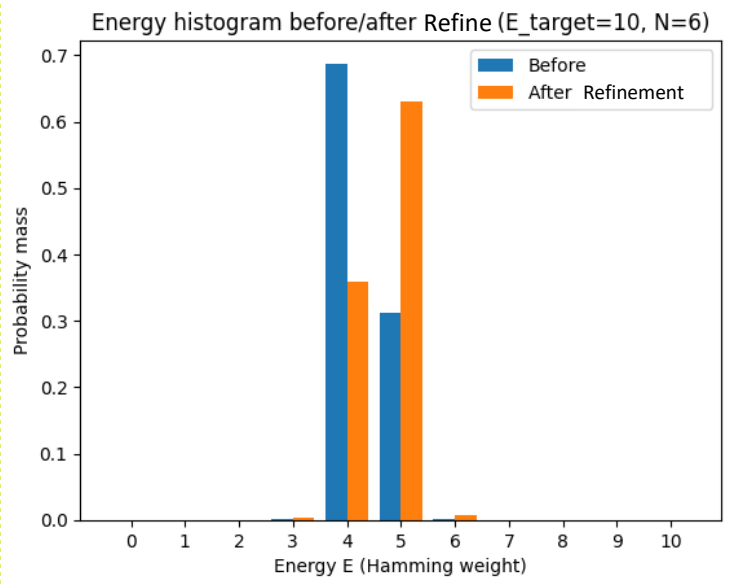
Possible to **embed graph topologies beyond** the limits of a **single device**

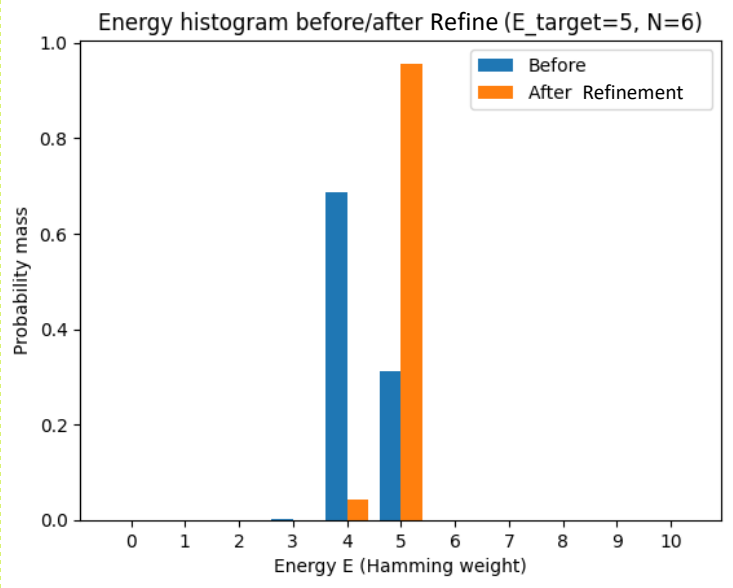
Objective: find a **natively Distributed Quantum Algorithm** able to **solve MIS problems on neutral atom QPUs**



More complex topologies



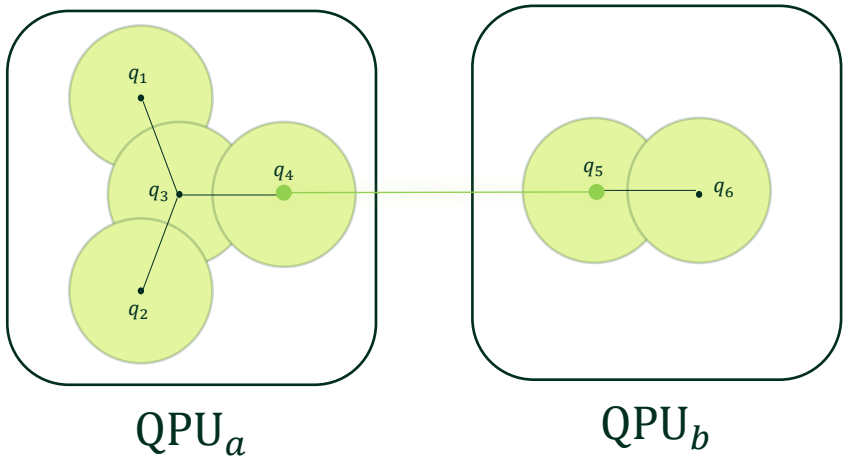




Distributed Quantum Algorithm for MIS on neutral atoms QPU

The Distributed approach works as follows:

- **Exploit property of MIS**: Long edges broken into smaller edges with the use of additional nodes
- **Entangled pair** provided by the link are used to **physically implement such MIS property**



DISTRIBUTED QUANTUM ALGORITHMS: PDE AND MIS PROBLEMS

Conclusions

- **Distributed quantum computing** (DQC) offer a viable **path to scalability** via **interconnecting smaller QPUs with quantum links** providing **entanglement**

- In the near term, it is crucial to study **natively Distributed Quantum Algorithms** to **reduce** the **distribution cost and extend the range of possible applications**

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