Tutorial on Variational Quantum Algorithms for Resource Management in Cloud/Edge Architectures

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ABSTRACT

This tutorial offers a practical introduction to the fascinating world of quantum computation and its application to optimization and machine learning problems. The participants will acquire hands-on experience in developing hybrid "Variational Quantum Algorithms", which combine classical and quantum computation, and in running them both on simulators and real quantum hardware provided by leading ICT companies. As a concrete use-case, of specific interest for the HPDC community, the tutorial will discuss the optimal assignment and scheduling of resources on the different nodes and layers of a Cloud/Edge architecture, a problem that is known to have NP-hard complexity.

The tutorial will show how Variational Quantum Algorithms can become a viable alternative to classical algorithms to solve the resource assignment problem. The participants will be driven, step-by-step, to the reformulation of the problem in terms of an Ising problem, which is then solved through two variational quantum algorithms, i.e., Quantum Approximate Optimization Algorithm (QAOA) and Variational Quantum Eigensolver (VQE), by exploiting the libraries of IBM Qiskit and Xanadu Pennylane. Finally, the tutorial will discuss the perspectives on the use of quantum computation for this and other scenarios, and the possible avenues for future academic research and industrial developments.

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1 TUTORIAL TOPICS

The tutorial introduces the main novelties in the field of Quantum Computation, which is attracting interest both in the research and industrial communities due to the recent availability of quantum hardware capable of computing on a growing number of qubits. However, quantum hardware is currently noise-prone, and thus, there is a need for exploiting techniques, like hybrid and variational quantum algorithms, that could take advantage of quantum computation in the current Noisy Intermediate-Scale Quantum (NISQ) era. The following topics are covered in the tutorial:

- Definition, representation and measurement of qubits and quantum registers;
- Basic quantum gates: bit flip (X or NOT), phase flip (Z), Hadamard (H), rotations, controlled-NOT;
- Quantum entanglement and quantum interference;
- Quantum circuits: designing and modeling;
- Hybrid (classical/quantum) algorithms and their use for optimization and machine learning;
- Reformulation of integer linear programming (ILP) problems as Quadratric Unconstrained Binary Optmization (QUBO) and Ising problems;
- Development and execution of two specific Variational Quantum Algorithms: QAOA and VQE;
- Use of QAOA and VQE to solve the process allocation problem for Cloud/Edge architectures;
- Performance assessment of QAOA and VQE;
- Future perspective on the use of quantum algorithms for different application scenarios.

In the following, we briefly describe two of the main aspects covered in this tutorial: the role of Quantum Computing in a Cloud/Edge architecture, in Section 2, and the definition of the assignment problem through a formulation that can be tackled by quantum algorithms, in Section 3.

2 QUANTUM COMPUTING FOR EDGE/CLOUD

Recently, new paradigms are emerging to distribute the computation among centralized and decentralized nodes, exploiting heterogeneous types of platforms, with very different capabilities and characteristics: sensors/actuators, mobile devices, personal computers, Cloud data centers, etc. The so-called continuous computing architecture [2] aims to integrate all these platforms and foster their cooperation. A computing architecture that includes quantum computers is shown in Figure 1. It is composed of: (i) a *device layer*, which includes sensors/actuators and smart objects; (ii) an *Edge/Fog layer*, which includes Edge nodes located close to the devices and (iii) a *Cloud/Quantum layer* that includes Cloud infrastructures and quantum computing devices.

The efficient and flexible management of this architecture relies on resource management algorithms. In particular, it needs to be determined which processes can be executed on Edge nodes, respecting their constraints, and which should be offloaded to the Cloud [1]. Quantum Computing algorithms can help to tackle assignment problems of this kind. Quantum computers leverage the intrinsic parallel nature of quantum operations: in particular, an operation can be performed on a number of configurations that is exponential with respect to the number of adopted resources, i.e., the qubits. Today, the most promising approach is to devise

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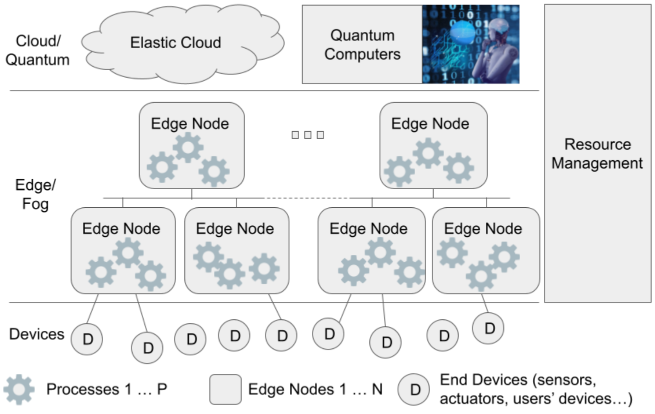

Figure 1: Quantum/Edge/Cloud computing continuum.

variational hybrid algorithms [3, 5], in which quantum computation is driven by a set of parameters that are optimized classically, in a cycle that aims at finding the best solution with a significant speed-up with respect to classical approaches.

3 ASSIGNMENT PROBLEM

Given a set of processes $\mathcal{P} = \{1, ..., P\}$ and a set of Edge nodes $\mathcal{N} = \{1, ..., N\}$, there is the problem of assigning each process to an Edge node or to the Cloud. The execution of processes on Edge nodes can bring important benefits, for example, in terms of service latency and access to local data that have peculiar security and privacy characteristics. Therefore, the assignment needs to maximize the effectiveness of the processes, for example in terms of service latency, and at the same time it must take into account the limited availability of the computation resources on each node.

As detailed in [6], the problem can be formulated as a binary linear programming problem, which is known to be NP-hard. The problem is defined as follows:

$$\max \sum_{i \in \mathcal{P}, j \in \mathcal{N}} v_{ij} x_{ij} \tag{1}$$

$$\sum_{j \in \mathcal{N}} x_{ij} <= 1, \qquad \forall i \in \mathcal{P} \tag{2}$$

$$\sum_{i \in \mathcal{P}} w_i x_{ij} <= B_j, \qquad \forall j \in \mathcal{N} \tag{3}$$

The binary variable x_{ij} is equal to 1 if the process i is assigned to the Edge node j, and 0 otherwise. If a process i is not assigned to any Edge node, it is considered to be assigned to the Cloud. The objective is to assign the processes to nodes and maximize the overall gain function while matching the capacity constraints of the Edge nodes. Each process $i \in \mathcal{P}$ is assigned a value v_{ij}, which is the value gain of executing process i on a node $j \in \mathcal{N}$, w.r.t. executing the process on the Cloud (e.g., a measure of its effectiveness in terms of latency or occupied network bandwidth), and an integer weight w_i, which represents the amount of computing resources required by process i for its execution. Each Edge node j has a capacity B_j, defined as an integer. The Cloud has no constraints, as its capacity is considered much larger than the available Edge nodes. The tutorial shows how this problem can be transformed into an Ising problem [4] and solved by QAOA and VQE. The Ising problem can be formulated as:

$$min \left(\sum_{i=1}^{Q} h_i \cdot z_i - \sum_{i=1}^{Q} \sum_{j=1}^{i-1} J_{ij} \cdot z_i \cdot z_j \right) \tag{4}$$

where the binary variables have been substituted by Q discrete variables z, which can assume values $\{+1, -1\}$. Each discrete variable is associated with a qubit, and the quantum computing problem is defined over a registry of Q qubits. Starting from the Ising expression, a Hamiltonian operator is built with sums and tensor products of two basic one-qubit operators, i.e., the identity $\mathbf{I}$ and the Pauli operator $\mathbf{Z}$:

$$\mathbf{H} = \sum_{i=1}^{Q} h_i \cdot \mathbf{Z}_i - \sum_{i=1}^{Q} \sum_{j=1}^{i-1} J_{ij} \cdot \mathbf{Z}_i \otimes \mathbf{Z}_j \tag{5}$$

Now, the problem becomes finding the ground state of the Hamiltonian operator. A register of Q qubits is prepared to achieve with maximum probability the ground state, in which each qubit, after measurement, collapses to one of the basis states $|0\rangle$ or $|1\rangle$. The solution to the problem is obtained by setting each originary binary variable to 0 if the corresponding qubit collapses to $|0\rangle$ or to 1 if the corresponding qubit collapses to $|1\rangle$.

The tutorial shows how the QAOA and VQE algorithms are executed on quantum simulators and real hardware, and illustrates a performance comparison between the two algorithms. Moreover, the analysis of computing times of classical and quantum algorithms suggests that classical algorithms are faster, but the scalability behavior of quantum algorithms is better, opening perspectives about the possible achievement of a quantum speed-up when more powerful quantum computers will be available.

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REFERENCES

[1] Marica Amadeo, Antonella Molinaro, Stefano Yuri Paratore, Albino Altomare, Andrea Giordano, and Carlo Mastroianni. 2017. A Cloud of Things framework for smart home services based on Information Centric Networking. In *2017 IEEE 14th International Conference on Networking, Sensing and Control (ICNSC)*. 245–250.

[2] Luciano Baresi, Danilo Filgueira Mendonça, Martin Garriga, Sam Guinea, and Giovanni Quattrocchi. 2019. A unified model for the mobile-edge-cloud continuum. *ACM Transactions on Internet Technology (TOIT)* 19, 2 (2019), 1–21.

[3] Marco Cerezo, Andrew Arrasmith, Ryan Babbush, Simon C Benjamin, Suguru Endo, Keisuke Fujii, Jarrod R McClean, Kosuke Mitarai, Xiao Yuan, Lukasz Cincio, et al. 2021. Variational quantum algorithms. *Nature Reviews Physics* 3, 9 (2021).

[4] Barry A Cipra. 2000. The Ising model is NP-complete. *SIAM News* 33, 6 (2000).

[5] Carlo Mastroianni, Francesco Plastina, Luigi Scarcello, Jacopo Settino, and Andrea Vinci. 2024. Assessing Quantum Computing Performance for Energy Optimization in a Prosumer Community. *IEEE Transactions on Smart Grid* 15, 1 (2024), 444–456.

[6] Carlo Mastroianni, Luigi Scarcello, and Andrea Vinci. 2023. Quantum Computing Management of a Cloud/Edge Architecture. In *Proceedings of the 20th ACM International Conference on Computing Frontiers* (Bologna, Italy) *(CF '23)*. Association for Computing Machinery, New York, NY, USA, 193–196.