Quantum Scheduling Optimization for UAV-Enabled IoT Networks

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ABSTRACT

Quantum computing is a promising technology which is able to speed up computation, by several orders of magnitude, with respect to classical systems. In particular, quantum optimization can be employed to solve complex problems in many engineering fields. In this work, it is proposed to use Quantum Annealing (QA) to solve a binary optimization problem to derive an optimal scheduling plan in an Unmanned Aerial Vehicle (UAV)-enabled Internet of Things (IoT) network. Based on specific design criteria, specific problem formulation can be cast, thus providing real-time solutions.

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1 INTRODUCTION

Quantum computing [3], is a well-known paradigm that recently gained momentum since it is able to afford very large and complex simulations, thanks to quantum mechanics principles, such as superposition and entanglement. The building blocks of quantum computation are quantum bits (qubits). Unlike classical bits that can assume binary values, i.e., either 0 or 1, a quantum bit can be in a superposition of two values simultaneously, thus implying a huge computational performance improvement.

Drones, thanks to their flexibility and inherent mobility, are key enablers for different application scenarios, such as surveillance, product delivery, and flying Base Stations (BSs) [1]. Several telecommunications-related problems are NP-hard such as scheduling for radio access networks [5], which belongs to the class of combinatorial problems. In particular, in UAV-enabled IoT networks dedicated strategies to assign the network resources among nodes are required, thus satisfying a set of design principles, e.g., fair distribution, maximum sum-rate. Accordingly to its inherent characteristics, quantum computing is suitable to find an optimal scheduling plan in real-time. Nevertheless, currently, its employment is limited to shared platforms and requires specific methodologies to encode problems into quantum-compliant forms.

The most used algorithm to solve this type of optimization problems is QA in which the strength of a magnetic transverse field is used to prevent remaining stuck in local minima. At the end, QA stays close to the lowest energy level which corresponds to the optimal solution of the original problem.

Considering the promising potential of quantum computing, the project aims at deriving an optimal scheduling plan in a UAV-enabled IoT network by employing QA. Therefore, the following research questions arise:

- *What are the advantages of solving the reference NP-hard problem with quantum computing?*
- *Are there major trade-offs that would hinder the applicability of this technology to the aforementioned problem?*
- *What are the differences in terms of computational time and found solutions over classical approaches?*

To answer the above questions, an extensive research on QA and its implementation on a real quantum computer are required.

2 QUANTUM ANNEALING

QA is a metaheuristic search algorithm for finding the lowest energy level of a quantum system, which can be employed to solve an optimization problem formulated as a time-dependent Hamiltonian [4]. It begins by initializing all qubits in a superposition of all possible states and then it evolves following the time-dependent Hamiltonian of the system. This is composed by (i) the final Hamiltonian H_f, which corresponds to the optimal solution of the problem, and (ii) the initial Hamiltonian H_i, also called tunnelling Hamiltonian, that represents the lowest energy level in the initial state. The Hamiltonian scales by a time-dependent magnetic transverse field coefficient that goes from 1 to 0. This prevents the algorithm to remain stuck in local minima and allows to travel through barriers of high energy towards the ground state. Based on this hypothesis, a Quantum Processing Unit (QPU) implementing a quantum annealer, can be used to quickly reach the optimal solution. The lead company providing access to this powerful tool is D-Wave Systems, which offers APIs to easily deal with such an algorithm.

3 SYSTEM DESIGN AND DEVELOPMENT

The reference scenario considers a swarm of drones flying over a specific area, in which a certain number of Sensor Nodes (SNs) are deployed. Drones are in charge of gathering sensed data from nodes. Both UAVs and SNs are equipped with one antenna. It is assumed that all UAVs employ different sub-bands, i.e, Orthogonal Frequency Multiple Access (OFDMA) scheme is adopted. To further improve the resource allocation strategy, Time Division Multiple

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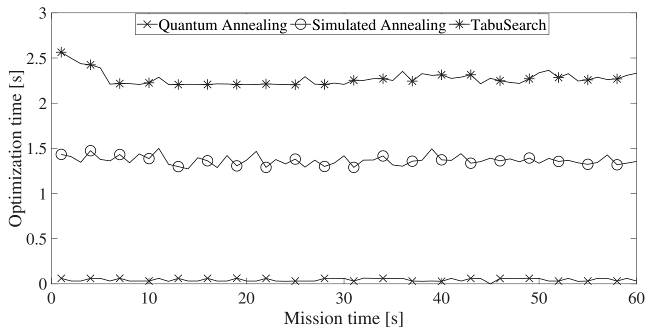

Figure 1: Preliminary comparison among different optimization algorithms.

Access (TDMA) is also adopted to enable simultaneous UAV-SN communications. In particular, the total mission time is divided into timeslots that are assigned to a specific link. The goal is to retrieve a scheduling plan such that resources are fairly allocated between nodes, in order to maximize the average data rate of the whole system. For instance, it can be dispatched by a quantum computer located in the cloud.

The above scheduling problem, initially defined in canonical form, can be solved by taking advantage of D-Wave's QPU, by performing the following three steps. In the first one, it is needed to map it into a Binary Quadratic form, i.e., either Ising Model or Quadratic Unconstrained Binary Optimization (QUBO), which are anyway exchangeable models. In the Ising model, variables are represented as a magnetic dipole moments of atomic spins which can be in either +1 or −1. It also requires, as input, a set of linear coefficients, called biases, and a set of quadratic coefficients, called coupling strengths. The former represents a set of values used to control an external magnetic field, which affects the probability of the qubits to fall in a particular state. The latter represents a set of values corresponding to the interaction between each couple of spins. Instead, the QUBO form, which is the most adopted one, considers the optimization variables as a binary vector x of size n and Q as an upper triangular matrix of real weights, thus leading to the definition of the objective function as $x^T Qx$.

Once the problem is mapped, in the second stage, an embedding phase is required to optimally load biases and weights in physical qubits. This is due to the fact that the objective function can be described also as a graph and the QPU is composed by a lattice of not fully interconnected qubits. This task can be easily performed manually, whereas the problem is characterized by few variables, or by employing heuristic approaches, such as MinorMiner [2], otherwise. In the last step, after initialization of hyperparameters, the problem can be executed by the QPU.

4 PRELIMINARY EVALUATION

To prove the advantages brought by quantum computing, a preliminary comparison with different classical algorithms, e.g., Simulated Annealing (SA) and Tabu Search (TS), has been carried out considered a simplified version of the reference problem. All the algorithms found a comparable solution in terms of throughput but, as depicted in Fig. 1, QA outperforms the competitors in terms of computational time. Nevertheless, certain aspects must be taken into account. In fact, to mitigate the communication and queue delay, a possible solution in a long-term vision, is to place QPUs at the edge of the network. Another issue is related to the embedding process that, in case of large problems, can hinder the convergence in a proper time. The next steps consist of solving the original problem by tuning hyperparameters and by investigating also hybrid quantum-classical approaches.

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