Quantum-related approaches for solving optimization problems: from applications to backend

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Quantum computing has emerged as an innovative paradigm with the potential to revolutionize optimization, through the exploitation of quantum mechanics phenomena. Several real-world problems across diverse domains, including finance, automatic control systems, machine learning, telecommunications, and mobility, can be handled as optimization problems, making their solution crucial in many contexts. Even though classical computing approaches have already made significant progress in solving these problems, quantum and quantum-inspired strategies offer new opportunities to reach outstanding performance, particularly for complex and high-dimensional optimization challenges.

The state of the art has already defined an overall conceptual workflow for quantum optimization, ranging from the problem formulation in a quantum-compliant way to the execution on one or more quantum or quantum-inspired solvers, passing through the mapping of an abstract model onto a target backends, depending on its physical and functional properties. However, these steps show some limitations, like the absence of tools for the automation of optimization problem formulation, a poor exploration of all the degrees of freedom associated with quantum solvers and the difficulties to accessing to real powerful quantum computers.

This doctoral thesis presents a comprehensive exploration of quantum and quantum-inspired methods for solving optimization problems, with the dual aim of advancing theoretical understanding and enabling practical applications. The research spans multiple levels of the computational stack, ranging from problem formulation and solver selection to algorithm development and hardware emulation. A central focus of the work is the description of real-world optimization problems into quantum-compliant formats, particularly using the Quadratic Unconstrained Binary Optimization (QUBO) model. Special attention is given to constraint management, real-valued variables, and parameter tuning to ensure that diverse and complex problems can be effectively represented and addressed using quantum and hybrid techniques, The thesis also presents some specific real-world use cases for which QUBO models have been defined: users scheduling in Joint-Transmission-based mobile networks and non-linear predictive control optimization.

For what concerns the model-to-backend mapping, the thesis reports the results of a research work looking at improving the Grover Adaptive Search (GAS) solver, taking into account its degrees of freedom, and the proposal of the MQT QAO framework for assisting end users in the leveraging quantum solvers. Moreover, it is also important to highlight that a supervised machine learning approach for solver selection is presented.

From an algorithmic perspective, the thesis explores the design and evaluation of new hybrid quantum-classical solvers, which exhibit improved performance in exploring rugged and heterogeneous solution landscapes. On the hardware side, the work explores ideal quantum computer emulation, evaluating the feasibility of quantum circuit emulation on low-tier Field-Programmable Gate Arrays (FPGAs), and proposes a highly parallel architecture for Simulated Bifurcation, a quantum-inspired optimization algorithm. This research creates a pipeline that begins with the mathematical abstraction of an optimization problem and extends to its deployment on custom architectures designed for quantum circuit execution.