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Quantum Computing applications tackling nowaday's problems

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Research context and motivation

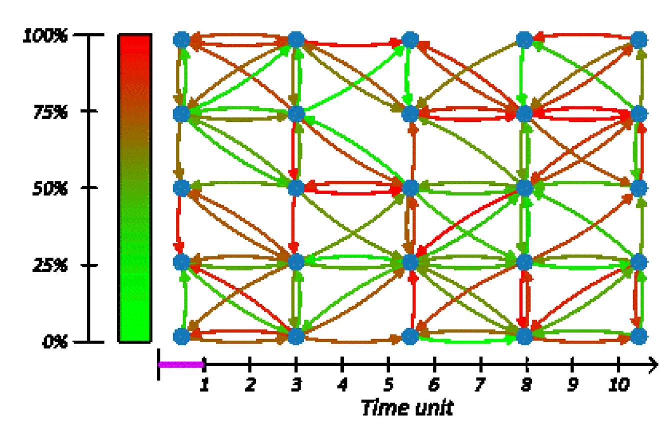
Over the past decades, there has been a growing interest in the field of Quantum Computing (QC). Among the various topics addressed by the research in its broad scenario, there is also the need to identify new applications with a quantum advantage. In this context, my current research activity is funded, and it is articulated in three main research fields:

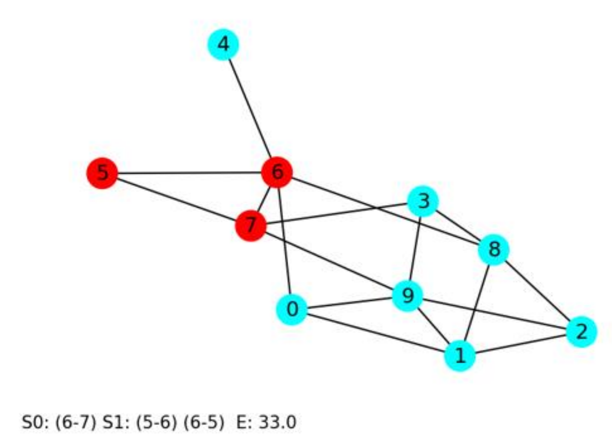
Ⓐ Quantum Optimizations
Ⓑ Quantum Machine Learning (QML)
Ⓒ Quantum Image Processing (QIMP)

Novel contributions

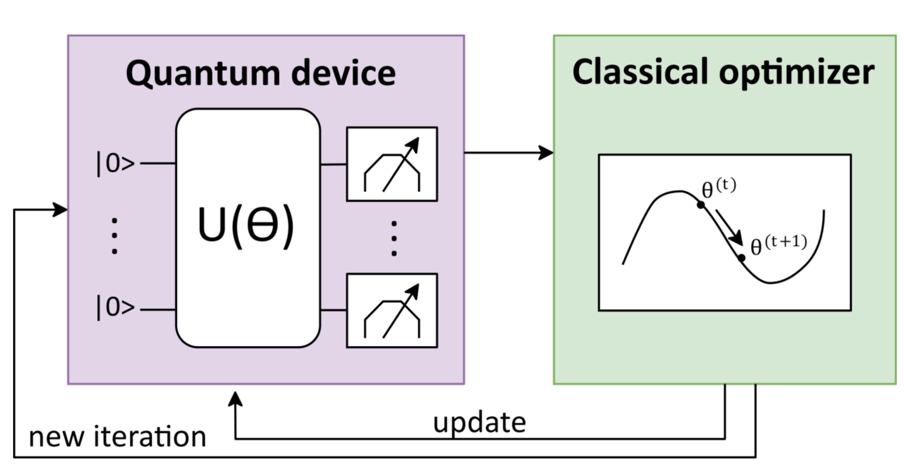
Ⓐ Two Quadratic Unconstrained Binary Optimization (QUBO) formulations have been proposed:

- In the smart mobility field, an optimization infrastructure has been defined to model the urban traffic evolution and to perform optimizations over it, reducing the congestion of the overall network. The tool is capable to generate random road networks, together with synthetic traffic data and to provide information on the optimal strategies to manage traffic fluxes. The conducted simulations have shown a promising reduction of the congestion ratio of the road networks.
- In the context of Virtual Network Functions, the QUBO model has been considered to optimize the embedding procedure of sets of network services in randomly generated physical network infrastructures. The optimization model has been solved both through classical techniques and quantum machines, proving the effectiveness of this last approach in terms of optimality, with respect to reference classical solutions.





Ⓑ The embedding techniques to perform supervised learning tasks have been investigated and benchmarked to identify the best solutions to represent classical information inside a quantum computer, with the aim to increase the quality of the final results. Two kinds of processing have been considered: Quantum Variational algorithms and Quantum Kernel functions, both hybrid classical-quantum techniques for near term application solutions. The results of this work can be considered to identify the best techniques to classify specific kind of data.



Ⓒ A quantum circuit library has been defined to allow users to compose in a modular way QIMP algorithms, with variable complexity, and extrapolating the key figures of merit to characterize the results. Among the available algorithms, some address computer vision tasks, like edge detection. The library has been enriched in classical processing techniques to experiment several pre-processing techniques to optimize the execution of the final quantum algorithms.

Submitted and published works

- Andrighetti, M., Turvani, G., Santoro, G., Vacca, M., Marchesin, A., Ottati, F., Ruo Roch, M., Graziano, M., and Zamboni, M. 2020. *"Data Processing and Information Classification—An In-Memory Approach"*. Sensors, 20(6).
- Marchesin, A., Turvani, G., Coluccio, A., Riente, F., Vacca, M., Roch, M., Graziano, M., and Zamboni, M. 2021. *"Octantis: An Exploration Tool for Beyond von Neumann architectures"*. In 2021 16th International Conference on Design & Technology of Integrated Systems in Nanoscale Era (DTIS) (pp. 1-5).
- Chiavassa, P., Marchesin, A., Pedone, I., Ferrari Dacrema, M., Cremonesi, P., *"Virtual Network Function Embedding with Quantum Annealing"*. In 2022 IEEE International Conference on Quantum Computing and Engineering (QCE).

Addressed research questions/problems

Ⓐ Two main problems have been addressed:

- Traffic optimization in a smart mobility scenario, to increase safety, and to reduce travel costs and the consequent environmental impact.
- The embedding of virtual resources on classical hardware in the context of network virtualization.

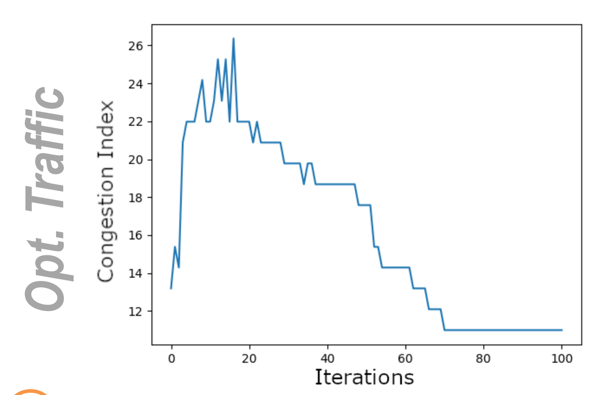
Ⓑ The idea is to identify the best QC strategies to encode the input data, taking into account the QC formalism, and to process them to perform the classification task.

Ⓒ There is a lack of uniformity in the characterization of QIMP techniques and there are no standard metrics for consistent comparisons, so it is difficult to identify the most promising.

Adopted methodologies

The literature of the problems faced has been deeply analyzed to understand the basic theory and the main criticalities, considered as possible opportunities for improvements.

Ⓐ For the optimization problems, QUBO formulations have been proposed. Then, simulation software environments have been arranged to test the models on large sets of application scenarios. The first tests, aimed at validating the models, have been conducted on heuristic simulators. Subsequently, the simulations have been focused on D-Wave Quantum Annealers to collect data on the quality of the solutions obtainable through these machines, and on the actual implementation perspective of the techniques proposed on them.

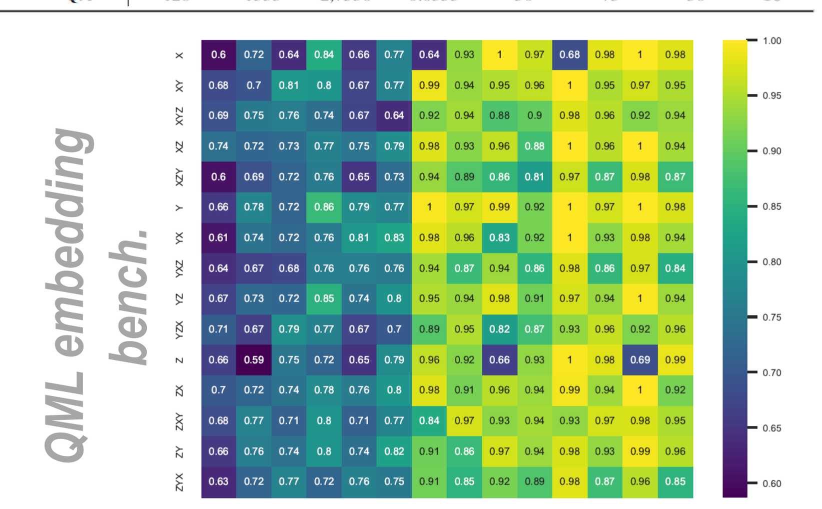


Opt. VNF Embedding

COMPARISON BETWEEN CLASSICAL SOLVERS AND QPU USING NET5 AND THREE SIMPLE SECAAS SERVICES.

Problem	Solver	QUBO variables	Qubits	Solver time (s)	QUBO time (s)	Chain Strength	Lowest Energy	QA time (s)	Reads
Allocation and Continuity Constraints Only	SA	72	-	0,1821	0,0021	-	0	-	10^2
	Tabu	72	-	2,1947	0,0021	-	0	-	10^2
	QA	72	250	0,0333	0,0021	50	0	50	10^2
Allocation and Continuity Constraints with Costs	SA	72	-	0,1862	0.0047	-	27	-	10^2
	Tabu	72	-	2,1319	0.0047	-	27	-	10^2
	QA	72	252	0,0299	0.0047	50	27	50	10^2
Full VNFEP Formulation	SA	128	-	0,3918	0.0355	-	27	-	10^2
	Tabu	128	-	2,1600	0.0355	-	27	-	10^2
	QA	128	1335	2,7550	0.0355	50	75	50	10^4

Ⓑ Several quantum circuits have been implemented to embed and process data following the quantum gate formalism. Two datasets (Iris and Wine) have been considered for the consequent benchmarking process and the results have been compared with those deriving from the application of traditional machine learning strategies, in terms of accuracy.



Ⓒ The algorithms selected for possible near-term applications have been implemented as modules of the library. Various tests have been carried out on each module to verify the correct implementation of the proposed techniques and to characterize their functioning.

Future work

Ⓐ The research activity on smart cities can be extended to realistic scenarios. Here, there is room for many other analyses and considerations on the consequences of applying the proposed optimization strategy to improve the quality of travel.

ⒷⒸ Starting from the analyses conducted, new models could be developed in both the QML and QIMP fields, trying to overcome the limitations of the techniques currently available.

Acknowledgments

My research activities are supported by TIM S.p.A. through the PhD scholarship. Moreover:

Ⓐ Interdisciplinary collaboration, resulted in the conference paper in references.
Ⓑ Implementation and benchmarking conducted by the thesis student, Antonio Tudisco.
Ⓒ Main modules defined within a thesis work, pursued by Chiara Dolciami.

List of attended classes

- UNITO – Experimental Implementation of Quantum Devices (15/02/21, 8h)
- 01QFFRV – Tecniche innovative per l'ottimizzazione (26/02/21, 20h)
- UNITO – Quantum Communication (24/05/21, 24h)
- 01TAHIU – Quantum computing (18/06/21, 20h)
- 01NOYOQ – Microelectronic systems (05/07/21, 60h)
- WEB – Qiskit Global Summer School (20/08/21, 30h)
- 01SHORV – Nano & Quantum Computing (16/12/21, 40h)
- POLIMI – Applied Quantum Machine Learning (27/04/22, 25h)
- 01DNHRV – System level low power techniques for IoT (15/07/22, 20h)

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