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Quantum-Assisted Multi-Objective Optimization of Heterogeneous Networks

by

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Dedicated to my parents, George and Vasiliki,
and to my sister, Kelly.

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

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Some of the Heterogeneous Network (HetNet) components may act autonomously for the sake of achieving the best possible performance. The attainable routing performance depends on a delicate balance of diverse and often conflicting Quality-of-Service (QoS) requirements. Finding the optimal solution typically becomes an NP-hard problem, as the network size increases in terms of the number of nodes. Moreover, the employment of user-defined utility functions for the aggregation of the different objective functions often leads to suboptimal solutions. On the other hand, Pareto Optimality is capable of amalgamating the different design objectives by relying on an element of elitism.

Although there is a plethora of bio-inspired algorithms that attempt to address the associated multi-component optimization problem, they often fail to generate all the routes constituting the Optimal Pareto Front (OPF). As a remedy, we initially propose an optimal multi-objective quantum-assisted algorithm, namely the Non-dominated Quantum Optimization (NDQO) algorithm, which evaluates the legitimate routes using the concept of Pareto Optimality at a reduced complexity. We then compare the performance of the NDQO algorithm to the state-of-the-art evolutionary algorithms, demonstrating that the NDQO algorithm achieves a near-optimal performance. Furthermore, we analytically derive the upper and lower bounds of the NDQO's algorithmic complexity, which is of the order of $O(N)$ and $O(N\sqrt{N})$ in the best- and worst-case scenario, respectively. This corresponds to a substantial complexity reduction of the NDQO from the order of $O(N^2)$ imposed by the brute-force (BF) method.

However again, as the number of nodes increases, the total number of routes increases exponentially, making its employment infeasible despite the complexity reduction offered. Therefore, we propose a novel optimal quantum-assisted algorithm, namely the Non-Dominated Quantum Iterative Optimization (NDQIO) algorithm, which exploits the synergy between the hardware parallelism and the quantum parallelism for the sake of achieving a further complexity reduction, which is on the order of $O(\sqrt{N})$ and $O(N\sqrt{N})$ in the best- and worst-case scenarios, respectively. Additionally, we provide simulation results for demonstrating that our NDQIO algorithm achieves an average complexity reduction of almost an order of magnitude compared to the near-optimal NDQO algorithm, while activating the same order of comparison operators.

Apart from the traditional QoS requirements, the network design also has to consider the nodes' user-centric social behavior. Hence, the employment of socially-aware load balancing becomes imperative for avoiding the potential formation of bottlenecks in the network's packet-flow. Therefore, we also propose a novel algorithm, referred to as the Multi-Objective Decomposition Quantum Optimization (MODQO) algorithm, which exploits the quantum parallelism to its full potential by exploiting the database correlations for performing multi-objective routing optimization, while at the same time balancing the tele-traffic load among the nodes without imposing a substantial degradation on the network's delay and power consumption. Furthermore, we introduce a novel socially-aware load balancing metric, namely the normalized entropy of the normalized composite betweenness of the associated socially-aware network, for striking a better trade-off between the network's delay and power consumption. We analytically prove that the MODQO algorithm achieves the full-search based accuracy at a significantly reduced complexity, which is several orders of magnitude lower than that of the full-search. Finally, we compare the MODQO algorithm to the classic NSGA-II evolutionary algorithm and demonstrate that the MODQO succeeds in halving the network's average delay, whilst simultaneously reducing the network's average power consumption by 6 dB without increasing the computational complexity.

Declaration of Authorship

I, **Dimitrios Alanis**, declare that the thesis entitled **Quantum-Assisted Multi-Objective Optimization of Heterogeneous Networks** and the work presented in it are my own and has been generated by me as the result of my own original research. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University;
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- Where I have consulted the published work of others, this is always clearly attributed;
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- Parts of this work have been published as: [1, 2, 3].

Signed: .... Date: ....

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List of Publications

Lead-Author Publications:

1. **D. Alanis**, P. Botsinis, S. X. Ng, and L. Hanzo, "Quantum-Assisted Routing Optimization for Self-Organizing Networks," *IEEE Access*, vol. 2, pp. 451–472, 2014. DOI: 10.1109/ACCESS.2014.2322013.

2. **D. Alanis**, P. Botsinis, Z. Babar, S. X. Ng, and L. Hanzo, "Non-Dominated Quantum Iterative Routing Optimization for Wireless Multihop Networks," *IEEE Access*, vol. 3, pp. 1704–1728, 2015. DOI: 10.1109/ACCESS.2015.2478793.

3. **D. Alanis**, J. Hu, P. Botsinis, Z. Babar, S. X. Ng, and L. Hanzo, "Quantum-Assisted Joint Multi-Objective Routing and Load Balancing for Socially-Aware Networks," *IEEE Access*, vol. 4, pp. 9993–10028, 2016. DOI: 10.1109/ACCESS.2016.2629671.

Additional Publications:

1. P. Botsinis, **D. Alanis**, S. X. Ng, and L. Hanzo, "Low-Complexity Soft-Output Quantum-Assisted Multiuser Detection for Direct-Sequence Spreading and Slow Subcarrier-Hopping Aided SDMA-OFDM Systems," *IEEE Access* , vol. 2, pp. 451–472, 2014. DOI: 10.1109/ACCESS.2014.2322013.

2. Z. Babar, P. Botsinis, **D. Alanis**, S. X. Ng, and L. Hanzo, "The Road From Classical to Quantum Codes: A Hashing Bound Approaching Design Procedure," *IEEE Access*,vol. 3, pp. 146–176, 2015. DOI: 10.1109/ACCESS.2015.2405533.

3. P. Botsinis, **D. Alanis**, Z. Babar, S. X. Ng, and L. Hanzo, "Iterative Quantum-Assisted Multi-User Detection for Multi-Carrier Interleave Division Multiple Access Systems ", *IEEE Transactions on Communications*,vol. 63, no. 10, pp. 3713-3727, Oct. 2015. DOI: 10.1109/TCOMM.2015.2458857.

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