

Potential Use-Cases in the Telecom Industry:

Emerging Optimization Problems in Telecom:

NB: This document is highly inspired from: [Mathematics| Quantum Computing in Telecommunication](#).

1. Introduction:

Discrete optimization problems that can be formulated as QUBO models are ubiquitous in the telecom industry. Hence, Quantum Annealing is a promising optimization method with fruitful and valuable real-world world applications in the telecom industry. Indeed, as we shall detail below, many abstract combinatorial optimization problems found concrete applications to optimize telecommunications networks. In addition, in many practical cases, the size and connectivity of the network allow for a direct implementation of the QUBO models on current Quantum Annealers, allowing for a full quantum treatment of the problem. Furthermore, when it is not the case, powerful hybrid solvers can still be used to tackle large optimization instances with up to a million of variables.

2. Main Applications Area of QUBOs:

To be more precise, real-world applications of Combinatorial Optimization in the Telecom Industry can be divided into 3 main areas: Network routing, Network Capacity (Resource Allocation) & Network Design and Planning.

a. Network Routing

Efficient routing of data packets to ensure fast and reliable communication. Optimisation algorithms are currently used to determine the best paths considering several practical constraints such as network congestion, latency or bandwidth allocation.

b. Network Capacity

Resource allocation is a crucial problem in the telecommunication industry. Indeed, telecommunication companies must allocate network resources efficiently to meet the varying demands of users. Hence, optimisation techniques are frequently employed to allocate bandwidth, spectrum, and other resources optimally, ensure efficient utilization and maximize network capacity.

c. Network design and planning

Building and expanding telecommunication networks require strategic decisions regarding the placement of base stations, antennas, and network infrastructure. Optimisation methods aid in determining optimal network configurations to minimize costs, maximize coverage, and meet Quality of Service (QoS) requirements. The last example is SLA Management. Telecommunication providers must adhere to SLAs that define quality metrics, such as network availability, latency, and throughput. Optimisation models help in managing SLAs by optimizing network resources and ensuring service guarantees are met.

3. Relevant General Problems:

a. Graph Coloring

The graph coloring problem is the first important problem for telecommunications since it finds practical applications in various areas of network design and optimization.

The graph coloring problem consists in assigning colors to the vertices of a graph such that no two adjacent vertices have the same color. In the context of telecommunications, the vertices of the graph can represent different elements of a telecommunication network, such as cell towers, antennas, or channels, while the edges represent the connections or interference between these elements.

A famous key application of graph coloring in telecommunications is frequency assignment for wireless communication systems. In wireless networks, different channels or frequency bands need to be assigned to different base stations or antennas to avoid interference between them. By representing the network as a graph, solutions of the graph coloring problem provide a suitable assignment of frequencies to minimize interference and maximize the overall capacity and performance of the network.

In addition, graph coloring is also relevant for optimizing other aspects of network design, like channel allocation, resource allocation, and scheduling. By appropriately coloring the graph representing the network, it becomes possible to efficiently allocate resources, schedule transmissions, and manage network resources to minimize congestion, improve efficiency, and enhance overall network performance.

Lastly, graph coloring is closely related to the concept of chromatic numbers, which quantifies the minimum number of colors needed to color a graph. Chromatic numbers are relevant in network planning and optimisation, as they provide insights into the requirements and limitations of a specific network configuration.

Quantum annealing has been successfully applied to solve the graph coloring problem [1]. In addition, thanks to the Rydberg blockade phenomenon, neutral-atom QPUs are a promising platform to solve graph optimization problems. Recently, a hybrid quantum-classical approach based on the traditional column generation approach was proposed in [2] to solve the graph coloring problem. For this study, an alternative approach to quantum annealing is proposed to solve the QUBO instances generated by the column generation algorithm.

b. Routing and the Traveling Salesman Problem(TSP)

Vehicle routing problems, including the traveling salesman problem (TSP) and its generalizations [1] are crucial in the field of telecommunications. Indeed, they are of practical relevance to optimize network efficiency, resource allocation, and overall system performance.

First the TSP involves finding the shortest possible route that visits a set of cities and returns to the starting point, while visiting each city only once. In the context of telecommunications, it can be used to find the most efficient routing paths for data packets or signals to traverse a telecommunication network of interconnected nodes,

such as routers or switches. Efficient routing is essential in telecommunications to minimize latency, reduce congestion, and optimize data transmission.

In addition, vehicle routing problems, which are variations of the TSP, are crucial for telecommunications companies since they can be used to design more efficient network architectures, plan optimal routing paths for data transmission, and improve the overall performance and reliability of their networks.

As examples, the Vehicle Routing Problem (VRP) and the Capacitated Vehicle Routing Problem (CVRP), are particularly relevant in logistical aspects of telecommunications, such as the deployment of service technicians, the delivery of equipment or resources, or fleet management. Efficient routing algorithms and optimisation techniques can help telecommunication companies reduce operational costs, improve service delivery times, enhance network scalability, and ensure the efficient utilization of available resources. Moreover, in the era of expanding communication networks and emerging technologies such as 5G and Internet of Things (IoT), the ability to solve routing problems efficiently and rapidly is crucial to manage the complex and dynamic flow of data within these networks.

The TSP and its variants have received a lot of attention and a detailed literature review of the quantum approaches to solving these problems can be found in [2].

c. Maximum Weighted Independent Set (MWIS)

The Maximum Weighted Independent Set (MWIS) problem holds significant importance in the field of telecommunications. The MWIS problem involves finding a subset of nodes in a network, such that no two nodes in the subset are directly connected, and the total weight of the selected nodes is maximized [1]. In the context of telecommunications, where network resources are often limited and need to be efficiently utilized, the MWIS problem is crucial for resource allocation.

Indeed, the MWIS problem is useful for mitigating interference, improving network efficiency, and enhancing overall system performance. It plays a key role in spectrum allocation, network planning, and resource management. Hence, it is an indispensable tool for achieving optimal utilization of telecommunication resources while ensuring reliable and high-quality communication services.

Quantum solutions for the MWIS problem have been proposed on different platforms: [2] relies on digital QC, quantum annealing has been explored in [3], photonic devices have been used in [4], finally neutral-atom QPUs are promising tools to solve MIS on unit-disk graphs thanks to the Rydberg Blockade phenomenon [5,6]

d. Maximum Weighted k-Clique

The Maximum Weighted k-Clique (MWkC) problem is another graph optimization problem of great significance in the field of telecommunications [1]. It aims at finding a subset of k nodes in a network that form complete subgraphs (cliques), where every node within a clique is directly connected to every other node. In telecommunications, MWkC has several crucial applications.

Indeed it can be applied to understand network topology, identify densely connected regions, or detect communities (or clusters of nodes with strong interconnectivity).

Thus, analyzing MWkCs allows telecommunication operators to gain insights into the underlying structure of their networks which can inform various tasks, such as network design, routing optimization, traffic engineering, and fault detection.

Moreover, maximum weighted k-cliques provide valuable information for resource allocation, capacity planning, and network resilience, allowing for more efficient and robust telecommunications systems.

In [2], a hybrid quantum approach combining parallel quantum annealing with graph decomposition is shown, allowing for solving large clique problems accurately.

e. Scheduling

The scheduling problem holds significant importance in the field of telecommunications. To be brief, scheduling problems are defined as finding the optimal assignment of a given set of jobs to a given set of workers, machines or processors [1].

Efficient scheduling is crucial for optimizing the utilization of network resources and ensuring smooth operations of communication systems.

To be more precise, various tasks such as allocating transmission slots, managing bandwidth allocation, coordinating channel access, and prioritizing traffic require effective scheduling. Thus, solving scheduling problems enables telecommunication companies to minimize latency, maximize throughput, and enhance the overall quality of service.

Moreover, emerging technologies such as 5G and beyond, require efficient scheduling to support diverse applications with varying quality-of-service requirements, enable the coexistence of different services and ensure the efficient use of the available spectrum.

In summary, the scheduling problem is essential for optimizing the performance, capacity, and reliability of telecommunications networks.

A quantum annealing approach for solving scheduling problems can be found in [2] while QAOA have been applied to scheduling in [3].

4. Some concrete practical examples:

a. Physical Cell Identifier Assignment:

Description:

The Physical Cell Identifier (PCI) is a fundamental parameter that identifies a specific cell within a cellular network. It is used by mobile devices to synchronize with and access a particular cell for communication. The PCI misassignments can lead to call drops, no voice/data connections, and other sorts of impairments. Therefore the PCI is crucial for proper cell identification, handover procedures, and interference mitigation.

In 4G cellular networks, the PCI assignment problem refers to the challenge of assigning unique PCI values to each cell in the network such that interference is minimal while efficient communication is ensured.

Challenges:

The PCI assignment problem is a complex optimization task which requires a

realistic modeling and a multi-objective approach to incorporate the operational constraints daily encountered in carrier-grade networks.

In addition, the problem becomes more complex in dense cellular network deployment, where a large number of cells are in close proximity. In this case, assigning unique and interference-free PCI values becomes challenging. This is because neighboring cells with similar or overlapping PCI values can cause interference, leading to decreased network performance, reduced signal quality, and potential communication issues for mobile devices.

Thus flexible and effective solvers capable of solving the PCI assignment more efficiently with reduced cost and computational time compared to current conventional optimization approaches are highly desirable to improve the efficiency of 4G networks.

Solution:

The PCI problem can be viewed as a modified graph coloring problem with additional constraints. Hence it can be formulated as a QUBO, and therefore be solved by the promising Quantum Annealing technique. Nevertheless, given the current limitations of commercial quantum annealers, large QUBO, relevant for real-world applications, are often impossible to directly map onto QPUs.

Decomposition into smaller and manageable subproblems is often needed to take advantage of QC even when using hybrid (classical-quantum) solvers or solvers that already apply decomposition techniques.

[1] proposed two heuristic decomposition algorithms to solve the Physical Cell Identifier (PCI) problem in 4G cellular networks in a way suitable for current quantum annealers are presented.

The first one solves the problem recursively through bisection (max-cut problem). It uses only one qubit to represent the status of the objects, avoiding one-hot encoding and thus minimizing the qubit requirement.

The second is a multi-step approach, finally solving sets of randomized modified max-k-cut problems of customizable qubit size.

These two algorithms have been applied to solve the PCI problem on real cellular networks including one of the main Italian national telecom operators (TIM).

The results show that all proposed QUBO approaches can be effectively applied to very large problems with similar or better performance than the reference classical algorithm, paving the way for the use on NISQ computers [1].

Potential Added-Value:

- Network Optimization.
- Ensure efficient Cell searches.
- Ensure efficient interface management.
- Ensure efficient handover procedures.
- Minimize interference.
- Increased Client satisfaction.

b. Peak-to-Average Power Ratio Minimization

Description:

To tackle the increasing traffic, the current 5G systems employ Orthogonal Frequency Division Multiplexing (OFDM) due to its robustness to channel fading, high spectral efficiency, and better multiplexing capability to multiple users. OFDM can however be prone to high Peak-to Average Power Ratio (PAPR). This means that a certain number of outgoing waveforms will feature a high (maximal) peak in

their power spectrum in relation to their average power, prior to being sent to the users.

This in turn pushes the High Power Amplifiers (HPAs) to work in their non-linear regime and consequently introduces distortions to the transmitted signals. The distortions introduce errors to the information carried by the waveform and so inadvertently also to the received data by the users. High PAPR might hinder this, but another source of error comes from the signal interfering with the environment. As the signal travels to the user, it may take multiple paths with various phase changes; making it more difficult for the users to decipher (decode) the information correctly.

These errors can be quantified by Error Vector Magnitude (EVM), on which there are industry standards called 3GPP requirements. The EVM requirement quantifies that users receive the information that was sent to them, up to some industry given standard. Hence, to mitigate these issues, and meet the 3GPP requirements, PAPR minimisation techniques are desirable.

Challenges:

First, the PAPR minimization is a non-convex problem and therefore a hard combinatorial optimization problem. In fact it is **at least** a NP-Hard problem.

Second, minimizing PAPR improves the quality of the transmitted signals, which may entail lowering the EVM. However, minimal PAPR is not a guarantee for the EVM to lie below the 3GPP requirements. Hence in practice, the minimisation of Peak-to-Average-Power-Ratio (PAPR) has to be performed so the 3GPP EVM standards are met. It results in an even harder combinatorial optimization problem with additional constraints.

Solution:

In [1] the PAPR minimization subject to the 3GPP EVM constraint is formulated as a QUBO model therefore amenable to Quantum Annealing. D-Wave Quantum annealers are then used to solve the constrained PAPR minimization.

The technique is applied to a toy model of 2x2 Multiple-Input-Multiple-Output (MIMO) system. The results of this work show that QA performs better than SA in terms of quality and runtime.

Nevertheless, due the qubit overhead introduced by quadratization of the original linear programming problem modeling the constraint PAPR minimization, scaling the method to larger instances remains challenging and other quadratization schemes and/or hybrid solvers could be beneficial.

Potential Added-Value:

Efficient PAPR minimization techniques capable of taking into account 3GPP constraints on EVM enable telecommunication operators to reduce distortions and errors, thereby improving system performance and efficiency and improving the user satisfaction.

In addition, a possible solution to deal with high PAPR is to increase power back-offs for the HPAs. However this introduces additional costs and lower the energy efficiency of the overall networks. Hence, PAPR minimization helps telecommunication companies to reduce both costs and energy consumption.

c. Vector Perturbation Precoding

Description:

Vector Perturbation Precoding (VPP) is a technique used in wireless communication systems, particularly in Multiple-Input Multiple-Output (MIMO) systems, to improve the performance and capacity of the system. In MIMO systems, multiple antennas are used at both the transmitter (base station) and receiver (user devices) to transmit and receive multiple data streams simultaneously.

Precoding techniques are employed at the transmitter to optimize the signal transmission and exploit the spatial diversity offered by the multiple antennas and multipath wireless channels.

VPP is a specific precoding technique that aims to improve the capacity of the MIMO system while maintaining a low-complexity implementation.

Challenges:

Finding an optimal perturbation in VPP is an NP-hard problem. Hence, it demands heavy computational resources at the base station which limits the feasibility of the approach to small MIMO systems. Using Quantum optimization approaches can therefore be advantageous and allows to enlarge the VPP approach to large MIMOs.

Quantum Approach:

In [1] a QUBO model for VPP optimization is derived and Quantum Annealing is applied to solve the VPP problem with D-Wave machines.

The results show that Quantum Annealing competes and can outperform state-of-the-art techniques for VPP like Zero Forcing and Fixed Sphere Encoder. In addition Quantum Annealing shows an advantage in terms of computational time while ensuring a satisfying solution.

Potential Added-Value:

Modern wireless networks are experiencing tremendous growth in traffic loads at base stations, and hence to meet the resulting computational and latency requirements, designers continue to investigate new architectures and hardware for today's 5G and tomorrow's 6G networks. A large component of cellular baseband processing comprises downlink data traffic due to a significant rise in the popularity and usage of video streaming platforms (e.g., Netflix). To meet the ever growing user demand, it is critical for the base stations to enhance the quality of downlink data streams in terms of throughput, error rate, and latency.

To that end, precoding techniques are used to eliminate the effect of inter-user interference and allow users to detect their respective data non-cooperatively, minimizing error-rate and maximizing throughput of MIMO downlink data transmission.

Although VPP has been shown to achieve better error performance compared to other precoding techniques, finding an optimal perturbation for user data in VPP is known to be NP-hard, making its implementation in massive/large MIMO systems to be infeasible.

In the near future, the approach of [1] could be enlarged to larger MIMO systems thanks to larger QPUs or by exploiting Hybrid solvers, or parallelism.

Hence, thanks to quantum optimization techniques VPP could be applied to large MIMOs which is currently unfeasible by classical means due the computational complexity of the task.

By improving the quality of the data streams in MIMO, VPP enables telecommunications to reduce error-rate and achieve enhanced throughput, thereby achieving better user experience and network efficiency.

d. Wavelength assignment Problem

Description:

In optical networks, the wavelength assignment problem arises in the context of wavelength-division multiplexing (WDM) technology. WDM enables the transmission of multiple optical signals simultaneously over a single optical fiber by using different wavelengths of light as carriers for each signal. The wavelength assignment problem involves determining which wavelengths (also known as channels) should be assigned to each connection or communication request in the network. This assignment needs to be done in a way that minimizes conflicts and ensures efficient utilization of the available channels. The goal is to assign wavelengths to connections in such a manner that there is no interference or crosstalk between them. Interference occurs when two or more connections share the same wavelength and their signals overlap, leading to signal degradation or loss. To avoid interference, each connection should be assigned a unique wavelength or a non-overlapping set of wavelengths.

Thus efficient wavelength assignment strategies are required to optimize network performance, minimize signal degradation, and maximize the number of connections that can be supported.

Challenge:

The wavelength assignment problem is a NP-Hard optimization problem that becomes more challenging as the network size and traffic demand increase. Hence, solving industry relevant cases is exponentially hard.

Conventional techniques, such as linear programming and mixed integer programming, may be useful, but the combinatorial nature and hardness of the problems make them extremely challenging to apply for large-scale problems of practical interest.

It is then reasonable to assume that the Wavelength Assignment problem might benefit from the use of quantum, hybrid or quantum-inspired techniques.

Quantum Approach:

In [1], the authors clearly show how the Wavelength Assignment problem (i.e. assigning wavelength to each transmissions for a fixed set or pre-computed paths) can be formulated as a Graph Coloring problem. Then, they also detail how to formulate the former Graph Coloring problem as a QUBO model.

Then, a quantum-inspired technique for solving QUBO is benchmarked against classical heuristic and industrial combinatorial solvers. Interestingly, the numerical results have indicated an advantage of the quantum-inspired solver in a number of test cases against the industrial combinatorial solver working on the

standard settings. Moreover, this work opens the way of solving this on real quantum annealers.

Potential Added-Value:

- Network performance optimization.
- Reduced number of required wavelengths.
- Minimize signal degradation
- Maximize number of transmissions/connections