Agile Earth Observation Satellite Scheduling with a Quantum Annealer

Presentation at COMET SIL

DEFENCE AND SPACE

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March 4, 2021

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AGENDA

- ❑ Context
  - ❑ Trends for agile Earth Observation satellite scheduling
  - ❑ Promises of quantum computing based optimization
- ❑ EO satellite scheduling with a Quantum Annealer
- ❑ Benchmarking methodology and results
- ❑ Conclusion and perspectives

Trends for Earth Observation Mission Planning

Trends Very High Resolution Agile EO Satellites

- Constellation of satellites: from 2-4 to 10s to 100s of platforms
- Smaller instrument footprint → larger volume of candidate meshes (i.e. surface elements) to plan per programming period
- Enhanced agility: multiplication of acquisition opportunities and planning solutions
- Multi-Objective optimization: priority satisfaction, capacity (surface) maximization, age of information, weather conditions…

Bottom line

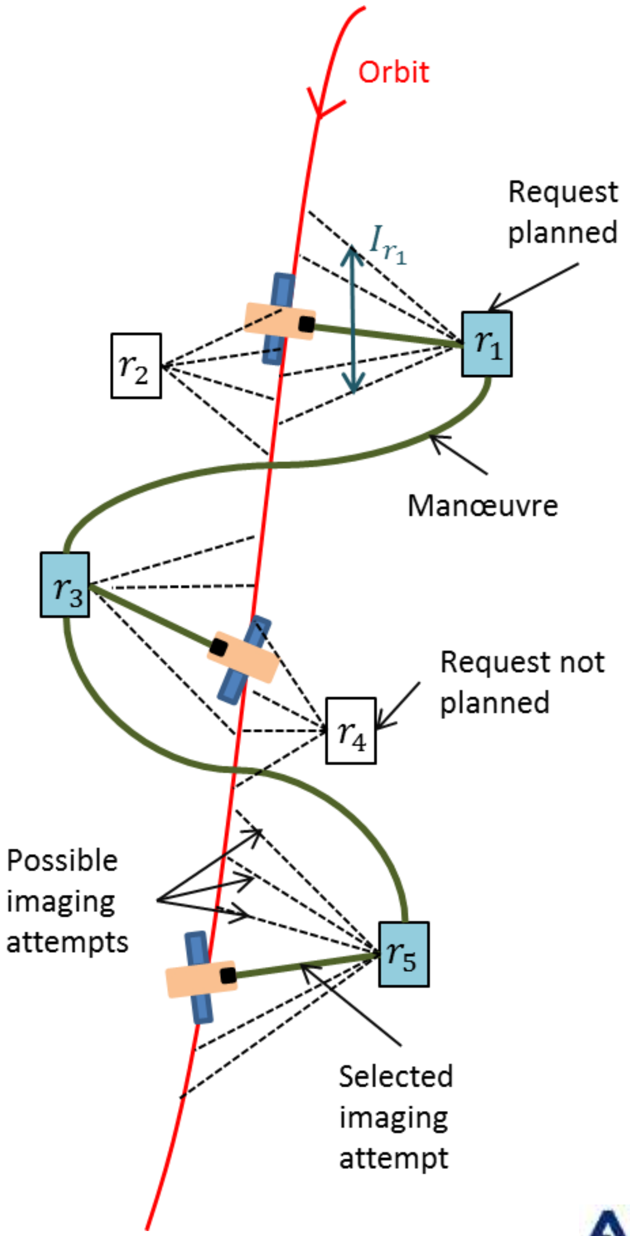
- EO Mission Planning is a well-known **multi-objective NP-hard optimization** problem **under uncertainty**
- Current trends indicate a **combinatorial explosion (# decision variables, # constraints)** for future Earth Observation systems

Expectations

- Current Mission Planning solutions are based on (sub-optimal) heuristic algorithms (greedy or dynamic programming)
- Experiments on smaller instances of the problem have shown gains ranging from 10% to 20% between the optimum and the solution obtained by current approximate algorithms

Simulation of Pleiades Neo Mission

EO Mission Planning Problem Statement



Mission Planning: Must determine an optimal acquisition plan for an Earth Observation satellite

Input data

- R is the set of acquisition requests, I_r is the set of imaging attempts for request $r \in R$.
- $\forall r \in R,\ \forall i \in\ I_r,\ w_{r,i}$ is the score of the imaging attempt
- $\forall r \in R,\ \forall i \in\ I_r,\ t_i^r$ is the start time of the imaging attempt

Decision variable

- $x_{r,i}$ is the binary variable indicating whether the candidate attempt i is selected in the plan
  - The number of binary variables is $\mathrm{N}_{\text{variable}} = \sum_r |I_r|$

Constraints

- Maximally one assigned attempt i per request r: $\forall r \in R,\ \sum_{i \in I_r} x_{r,i} \leq 1$
- Some consecutive imagining attempts are not possible:
  - $F_{r_1,r_2} = \{(i,j) \in (I_{r_1}, I_{r_2}) | t_i^{r_1} \leq\ t_j^{r_2}\ \&\&\ t_j^{r_2} < t_i^{r_1} + T_i^{r_1,acquisition} + T_{i \to j}^{r_1,r_2\ maneuver}\}$
  - $\forall (r_1, r_2) \in R^2, with\ r_1 \neq r_2, \forall (i,j) \in F_{r_1,r_2}:\ x_{r_1,i}.x_{r_2,j} = 0$

Objective: Total score of the schedule

- Minimize $C = -\sum_r \sum_{i \in I_r} w_{r,i} x_{r,i}$

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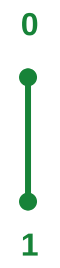
Quantum Computing in a Nutshell

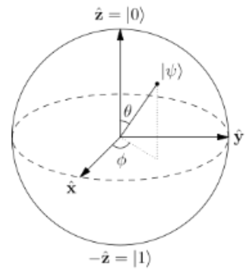
Superposition Principle

- A qubit can be seen as a superposition of two basis vectors

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

- A n-qubit register represents a 2^n-dimensional vector space, allowing for exponentially greater information processing





$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

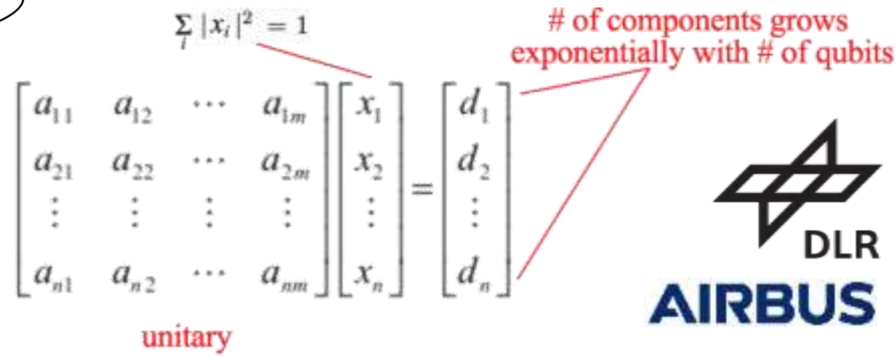
Classical bit

Quantum bit

Classical vs Quantum Computing

	Steps	Classical Computation	Quantum Computation
1	Initial State	A single length-N binary string e.g. **00**	Superposition of length-N binary strings e.g. $\frac{\|00\rangle+\|11\rangle}{\sqrt{2}}$
2	Apply Operations	Logic gates e.g. **00 → 01**	Quantum logic gates e.g. $\frac{\|00\rangle+\|11\rangle}{\sqrt{2}} \rightarrow \frac{\|10\rangle+\|01\rangle}{\sqrt{2}}$
3	Read Out	Read out e.g. **READ(01) → OBSERVED : 01**	Measure e.g. **MEASURE**$\left(\frac{\|10\rangle+\|01\rangle}{\sqrt{2}}\right)$ → **OBSERVED: either** 10 or 01

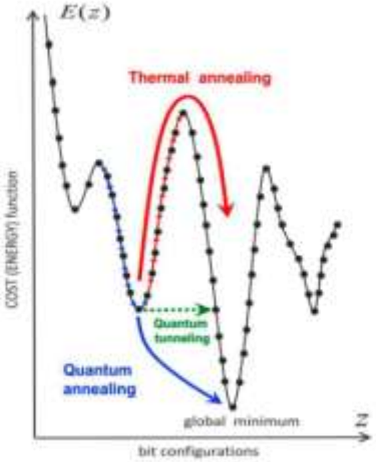
2^nx2^n Unitary operators



Quantum Computing in a Nutshell

Quantum Annealing Computer (D-Wave)

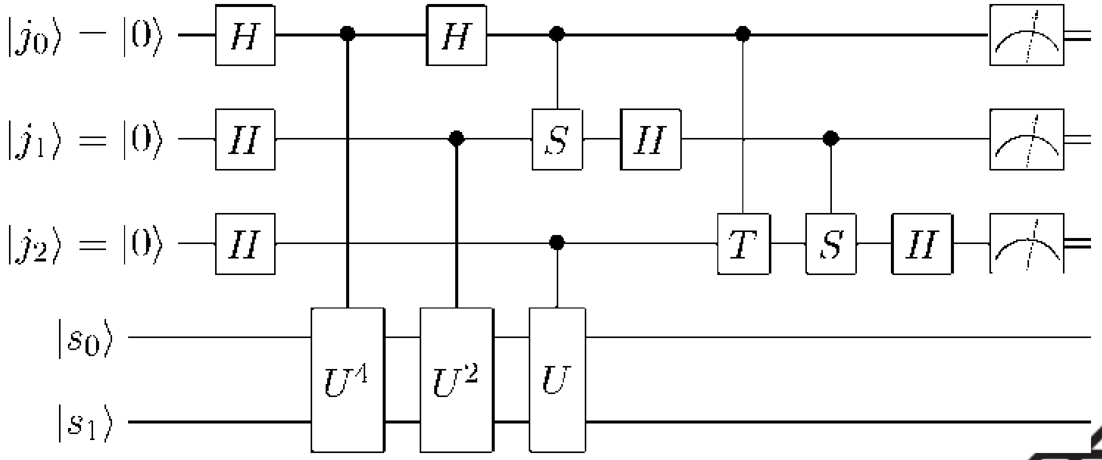
- Not a general purpose quantum computer, but uses quantum properties to solve discrete optimization problems
- Natural evolution of quantum-mechanical system (using quantum tunnelling) towards a ground state minimizing its energy



Quantum Annealer

General Purpose Quantum Computer (IBM, Google)

- Quantum circuits are composed of elementary gates and operate on qubits
- QC equivalent to classical boolean feed-forward networks, except they are reversible (i.e. quantum circuits can be evaluated in both directions)



Quantum Circuit

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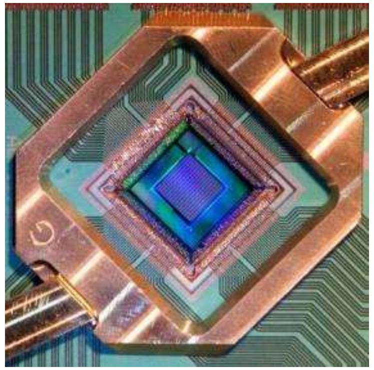
Airbus Amber

Quantum Annealer in a Nutshell



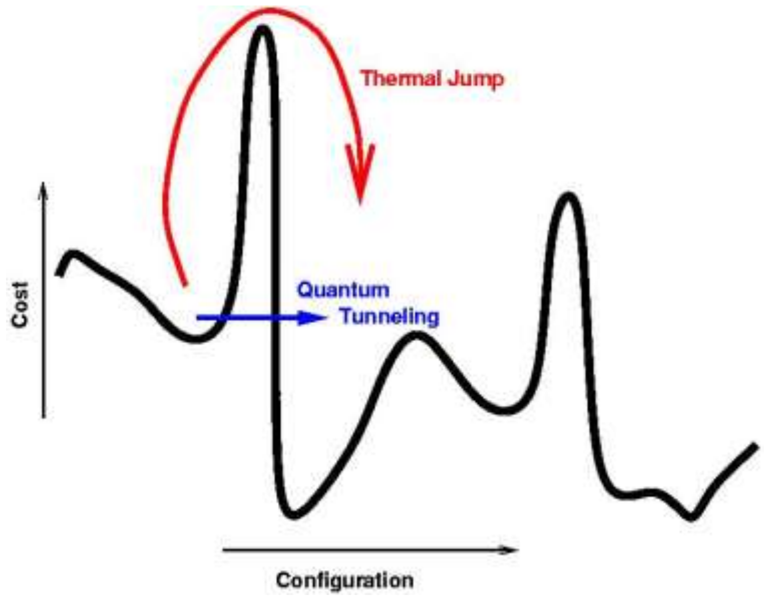
© D-Wave

Quantum Computing for Combinatorial Optimization

Quantum Annealing

- Solves Quadratic Unconstrained Binary Optimization (QUBO) problems
  i.e. minimmize $H(\{x_i\}) = \sum_i Q_{ii} x_i + \sum_{i<j} Q_{ij} x_i x_j$, where $x \in \{0,1\}^N$
- Requires to formulate your discrete optimization problem as a QUBO

- QA can be seen as a stochastic process: several annealing runs are performed from a given initial state (e.g. uniformly distributed quantum superposition of all possible states)
- After a fixed elapsed time, the final state is measured providing a solution sample
- After a fixed number of runs, the solution sample having minimum energy is kept
- QA remains an approximate optimization technique, but the number of runs can be increased to reach a given probability of finding the exact solution



Quantum Annealing

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EO Mission Planning Problem as a QUBO

Quadratic Unconstrained Binary Optimization (QUBO) formulation

- QUBO: $\min q(x) = x^T Qx = \sum_{j=1}^{n} Q_{j,j} x_j + \sum_{j,k=1}^{n} Q_{j,k} x_j x_k$ with Q an upper-triangular quadratic matrix

- Constraint equations in a quadratic form:
  - (1) : Max one imaging attempt per request : $C_u = \sum_r \sum_{i,j \in I_r, i<j} min\{w_{r,i}, w_{r,j}\} x_{r,i} x_{r,j}$
  - (2) : Non feasible maneuver $C_t = \sum_{r_1,r_2} \sum_{i,j \in F_{r_1,r_2}} min\{w_{r_1,i}, w_{r_2,j}\} x_{r_1,i} x_{r_2,j}$

- Constraints are taken into account in the QUBO formulation to minimize
  - $q = C + \lambda_u C_u + \lambda_t C_t$
  - With :
    - $C = -\sum_r \sum_{i \in I_r} w_{r,i} x_{r,i}$ is the objective function in the original problem
    - λ_u, λ_t are penalty weights

- Choice of the penalty weights
  - Sufficiently large enough such that $\hat{\boldsymbol{x}} = \arg\min_{\boldsymbol{x}} q(\boldsymbol{x})$ verifies our constraints, i.e. $C_u(\hat{\boldsymbol{x}}) = 0$ and $C_t(\hat{\boldsymbol{x}}) = 0$
  - We can demonstrate that any choice of penalty weight values such that both $\lambda_u > 1$ and $\lambda_t > 1$ gives valid solutions

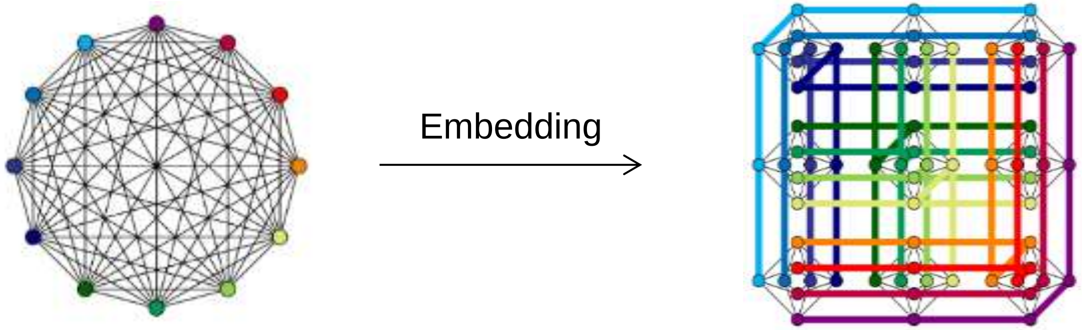
Mapping a logical QUBO into a physical QUBO

$$x_i \rightarrow \frac{s_i + 1}{2}$$

$$C = \sum_i h_i s_i + \sum_{ij} J_{ij} s_i s_j \xrightarrow{\text{Embedding}} C' = \sum_a h'_a s'_a + \sum_{ab} J'_{ab} s'_a s'_b$$

Embedding

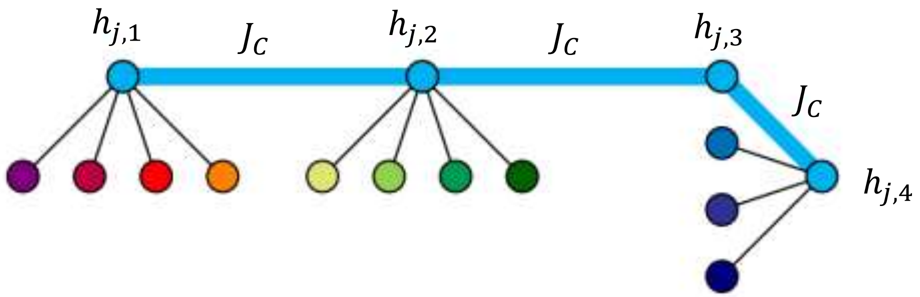
- Due to D-Wave architecture (chimera graph), a physical qubit is not connected to every other qubit
- Embedding is the process of linking physical qubits together to virtually enhance connectivity
- In our case, problem instances need to stay below 80 logical qubits to be embeddable on the D-Wave machine



Weight Distribution

- Couple physical qubits to chain
- Find chain coupling J_C
- Distribute weight h_j

- Classical Approach:
  - Choose J_C according to maximum coupling
  - Split weight equally $h_{j,i} \rightarrow \frac{h_j}{n}$
- Advanced Approaches:
  - Find minimal J_C without breaking chain
  - Map to problem of graph expansion



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Mission Planning Simulation

Problem Instances

Nb of requests = **11**
Discretization step = **12s**
Latitude range = **10°**

Nb of requests = **12**
Discretization step = **16s**
Latitude range = **1°**

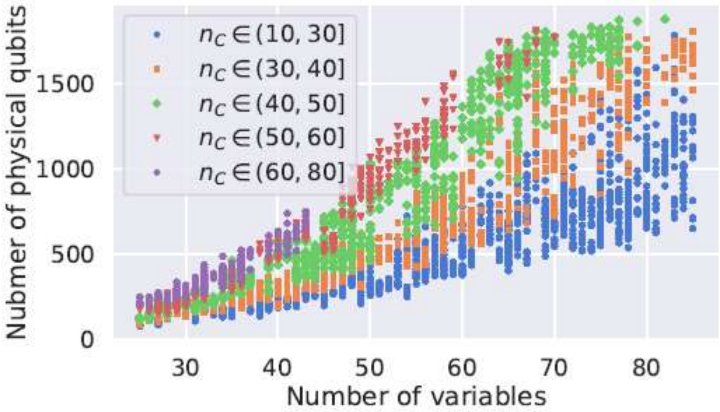
Mission Planning problem instances

- Generated thanks to Airbus DS Mission Simulator (TEAM)
- Reduced instances with a small number of requests and a coarse access discretization compared to real operations
- Different scenarios are considered to generate multiple instances, enabling sensitive analysis and statistics on average performance
- Main parameters
  - Number of acquisition requests
  - Access discretization step

  → Drives the number of decision variables

  - Latitude range for Area of Interest

  → Drives the "NP-hardness" of the planning problem



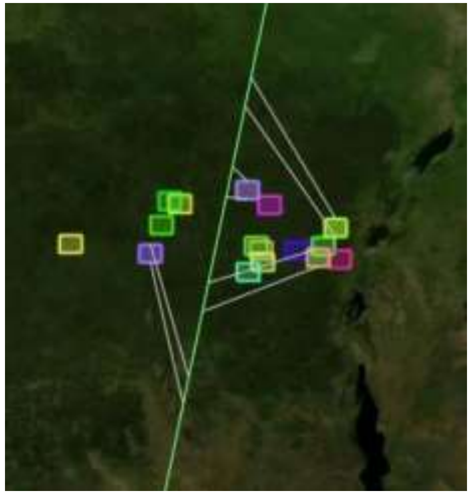
Outcome of Embedding

Evaluation on Classical Hardware

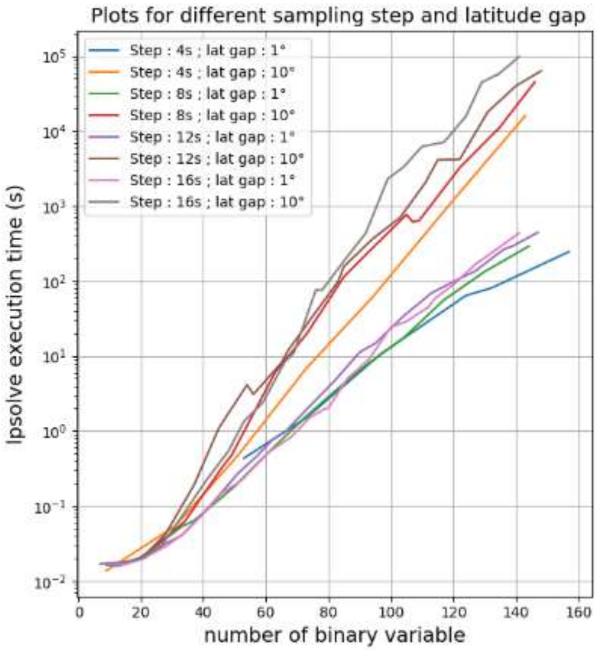
Two classical algorithm have been considered

- An exact MIP solver with two variants
  - pairwise exact solver: based on ILP where constraints correspond to pairs of conflicting attempts
  - clique exact solver: based on ILP where constraints are reformulated through the enumeration of all maximal cliques
- A greedy algorithm (similar to operational software), showing a linear runtime (at least for small instances)

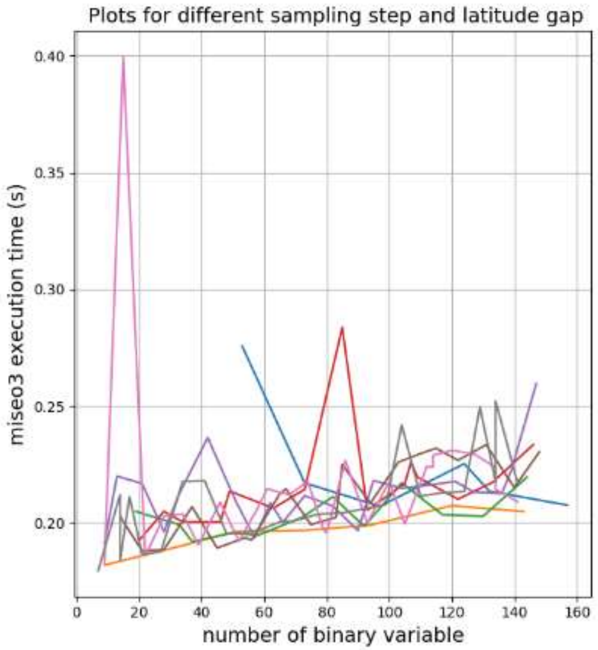
Exact solver



Greedy algorithm



Exact solver Run-time

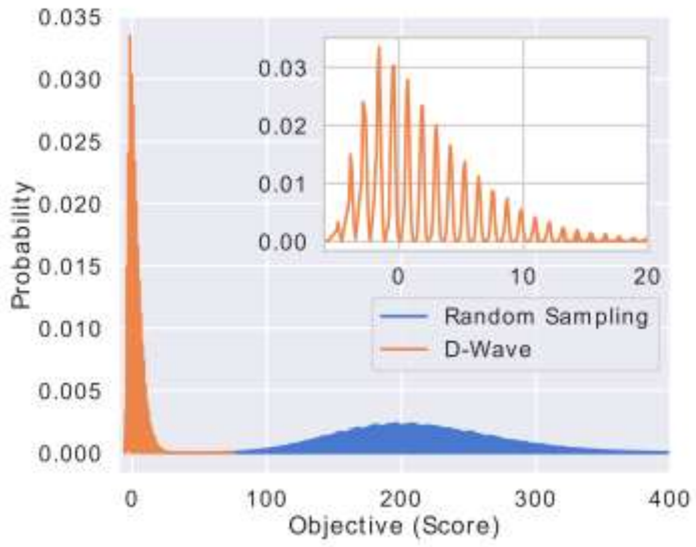


Greedy algorithm Run-time

Evaluation on D-Wave 2000Q Quantum Annealer

Performance Assessment methodology

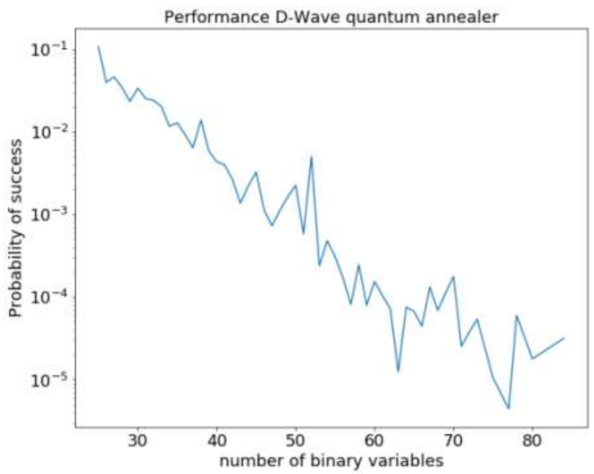
- A number of annealing runs is configured
- A success probability is derived: $p = \frac{\#\ exact\ solutions}{\#\ annealing\ runs}$ (probability to yield an optimal solution)
- Assuming independence between runs, a time-to-solution with 99% chance of optimality can be expressed as $T_{99} = \frac{\ln(1-0{,}99)}{\ln(1-p)} T_{Annealing}$



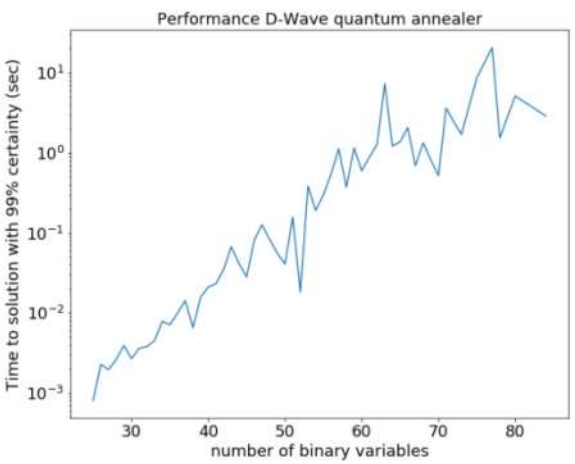
Random sampler vs D-Wave machine for QUBO resolution

D-Wave Configuration

- Number of annealing runs (10000)
- Annealing time (20 μs)
- Choice of intra-logical qubit coupling J_F
- Embeddings: using all 5 D-Wave heuristic embeddings
- Unembedding strategy: majority vote



Probability of success

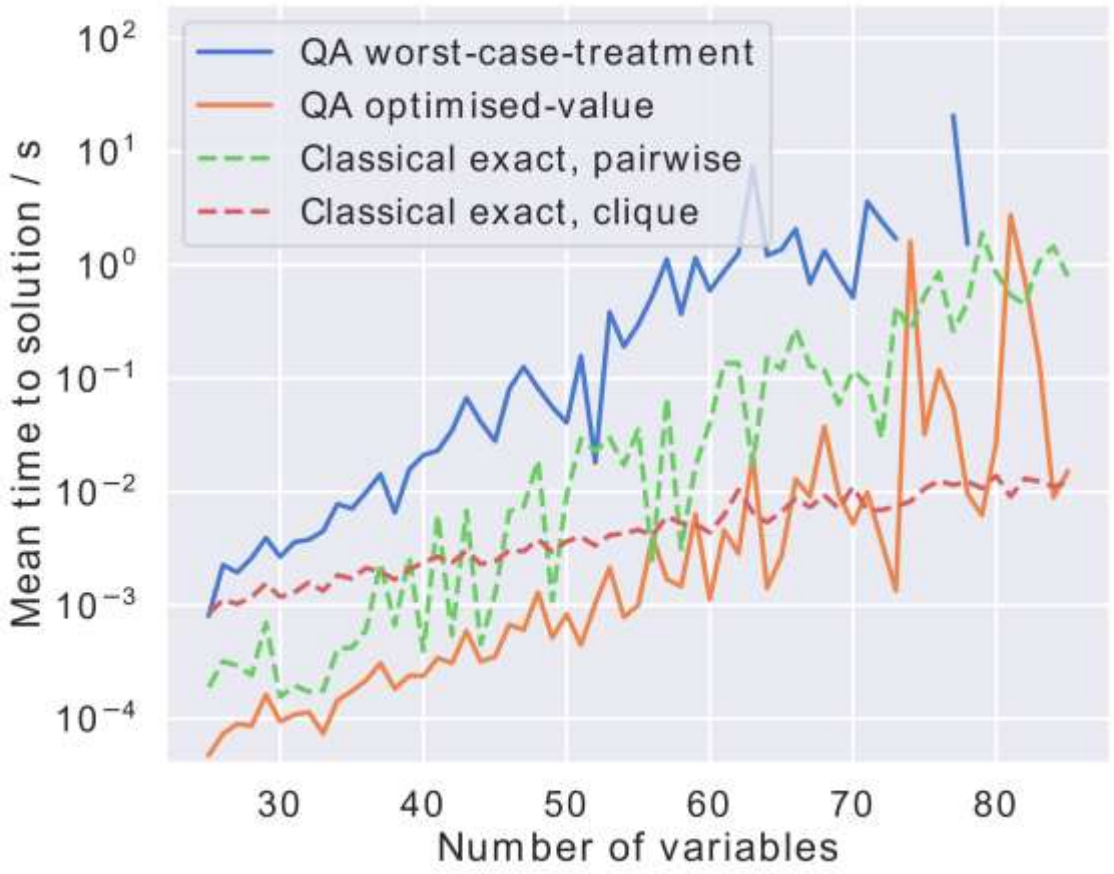


Time to solution with 99%

Benchmark 1: Classical vs Quantum Time to Exact Solution

Time to Exact Solution Benchmark

- Run time is averaged over all problem instances having the same number of binary variables
- Execution time for the pair-wise exact solver increases exponentially with the number of binary variables
- Quantum annealing results (worst-case treatment, i.e. classical weighting approach) shows a similar slope and a constant offset of about one order of magnitude.
- By optimizing the coupling chain strength (optimized-value), quantum annealing performs much better
- Clique exact solver performs better than all other methods for larger instances

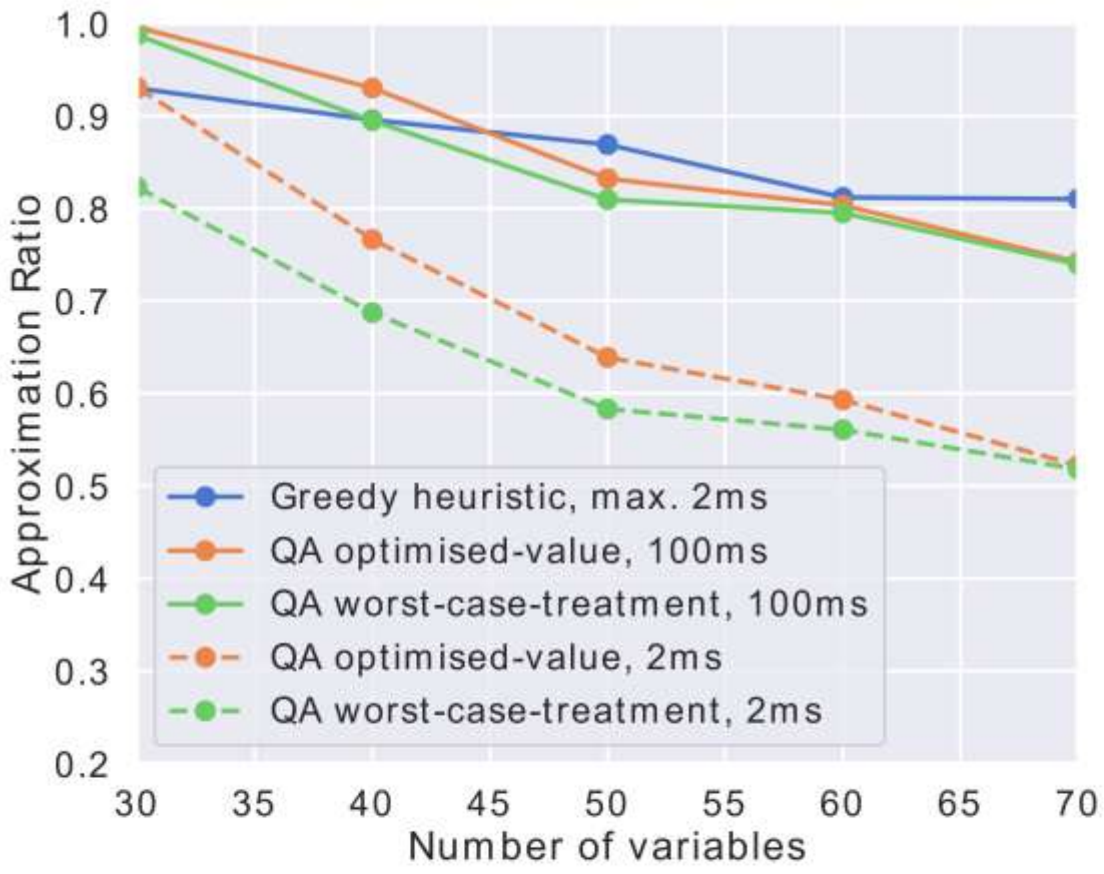


Time to exact solution benchmark

Benchmark 2: Classical vs Quantum Quality of Solution

Quality of Solution Benchmark

- A fixed time budget is allocated to the solver (.i.e a fixed number of runs for the quantum annealer)
- The approximation ratio corresponds to the objective value of the best found solution divided by the optimal objective value
- The greedy heuristic outperforms the quantum annealer for similar execution times
- Only for larger execution times, the quantum annealer yields better results than the greedy heuristic for smaller instances



Quality of solution benchmark

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Conclusion and Perspectives

arXiv paper: https://arxiv.org/abs/2006.09724

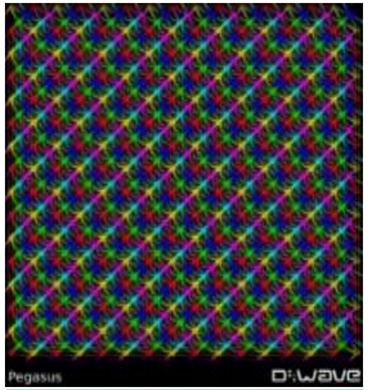
ESA Phi-Week

Technical achievements

- Classical vs Quantum benchmarks for a broad range of (small) satellite mission planning problems
- Limited qubit connectivity, **precision issues** and coherence time remain a major bottleneck for the D-Wave 2000Q processor.
- Although **no quantum speedup** was observed, the run-time performance on D-Wave Q Annealer (at its current scale) is very promising

Perspectives

- Extra research will be required to make a better use of Q technology (embedding techniques and mitigation of precision/errors for QA)
- To draw further conclusions, we need the Q technology (HW and SW) to **increase in maturity**, which will happen in a short timeframe
  - D-Wave Pegasus showcasing 5000 qubits and 16-connectivity
  - QAOA on Google Sycamore and IBM Q 53-qubit machines



D-Wave Pegasus


Google Sycamore

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Thank you