Finding water on Mars

using Quantum Computing

Quantum BC team

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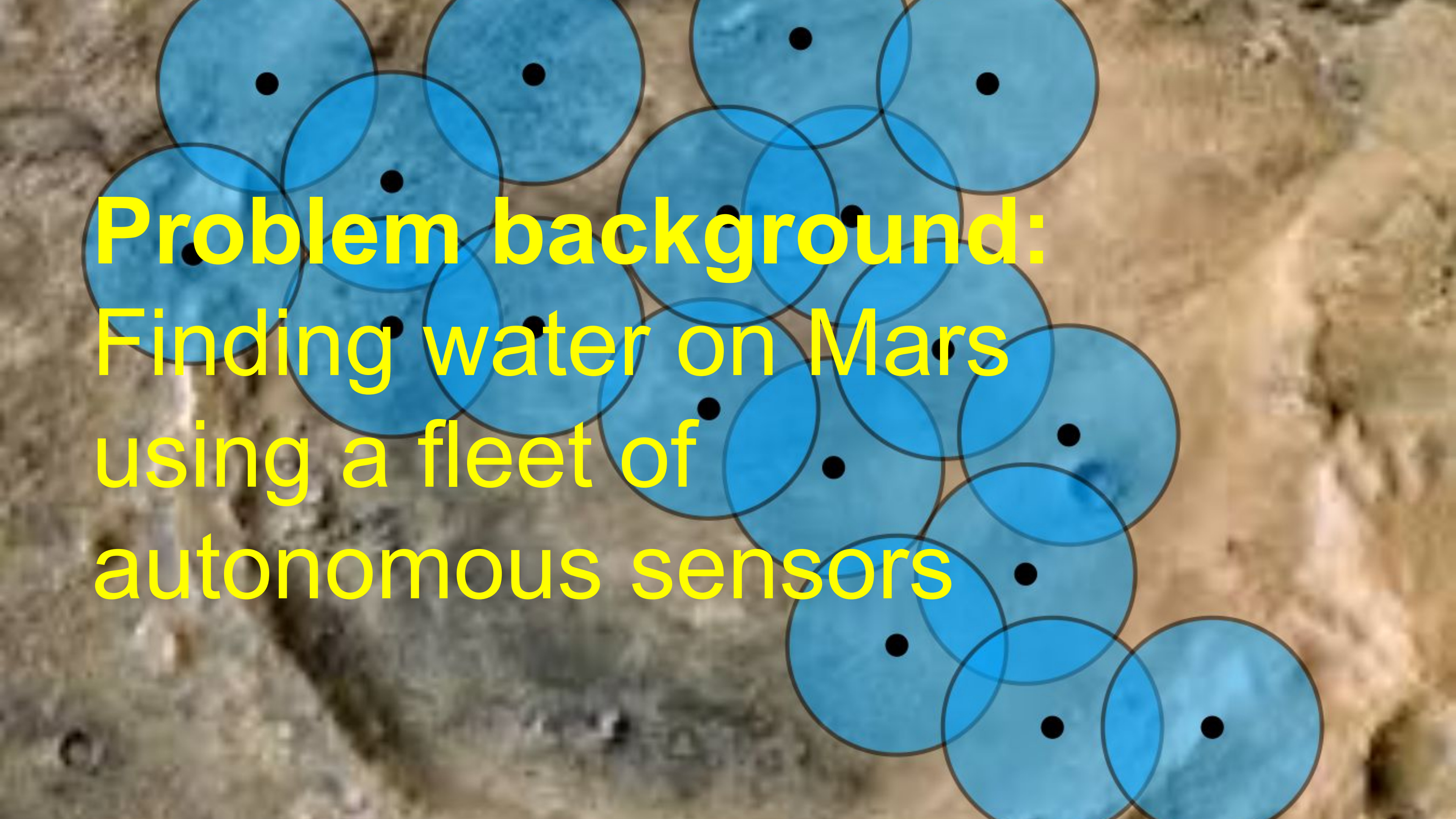


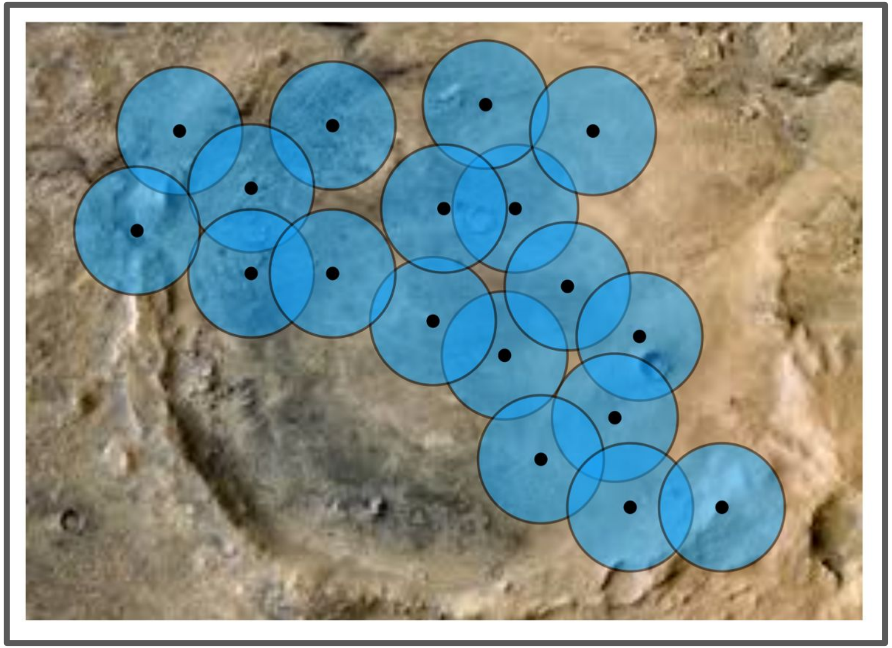
Problem background:

Finding water on Mars using a fleet of autonomous sensors

Mobile Ad-Hoc Networks on Mars

Idea : Use a fleet of autonomous nano-sensors to collectively explore areas

Problem : Short connection range of sensor poses a problem for global communication

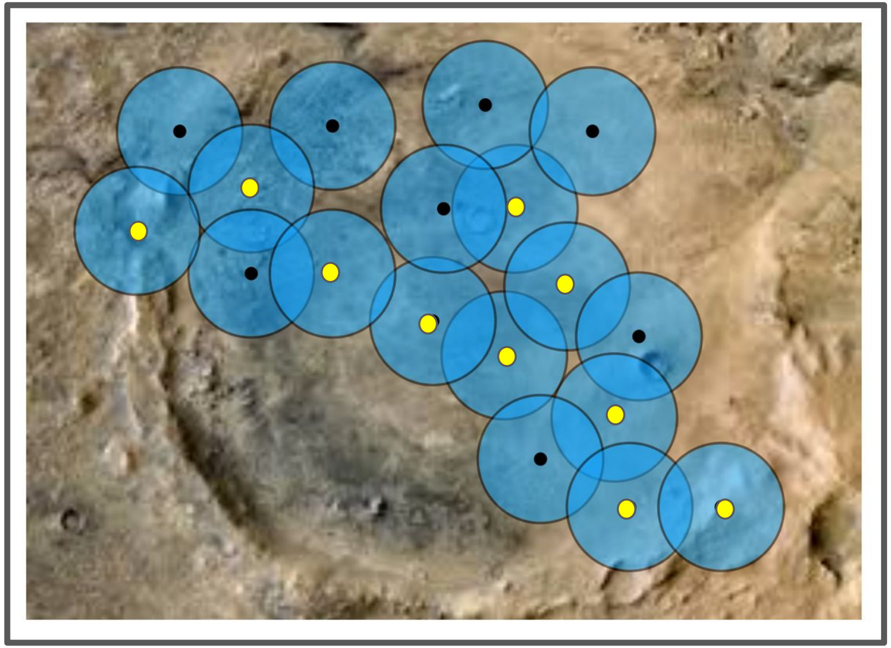


Mobile Ad-Hoc Networks on Mars

Define a **virtual backbone** of nodes in transmitter mode

Remaining nodes save energy by only doing the sensing task

Global communication is guaranteed



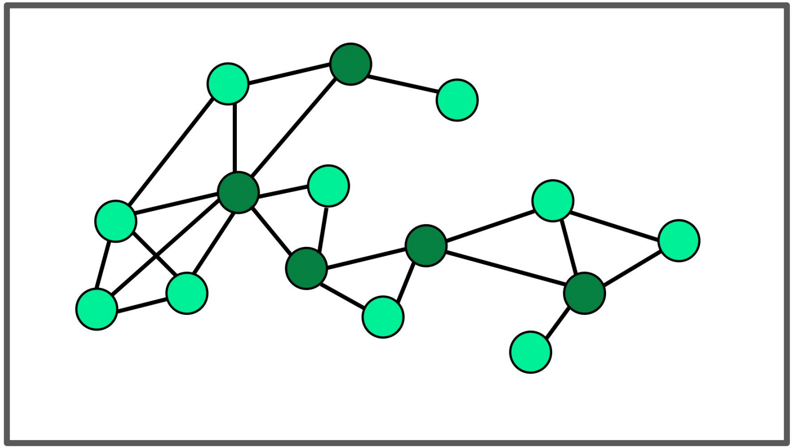
Connected Dominant Set

Graph **G** = (**V**, **E**)

Connected Dominant Set (**CDS**) is a subset **D** ⊂ **V** such that

- All vertices in **D** are connected
- Each node in **V/D** is a neighbor of at least one node in **D**

Finding the CDS of a graph is NP-hard i.e. $\mathbf{O(1.9407^n)}$



Technical goal : Find a "good" CDS of a graph using the capabilities of neutral atoms and Pulser

The challenge

Start with a **simple graph** for which the solution can be easily verified

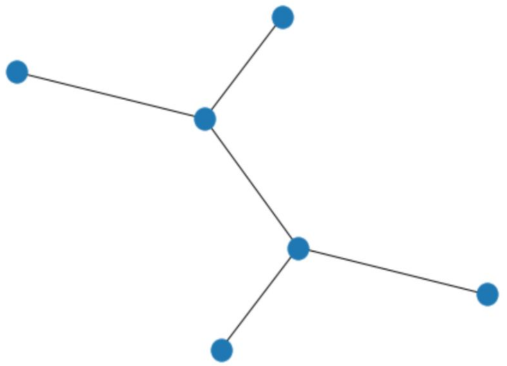
Develop solution to determine the **CDS** of the graph using **neutral atom quantum computing**

Generalize the approach to more complicated graphs

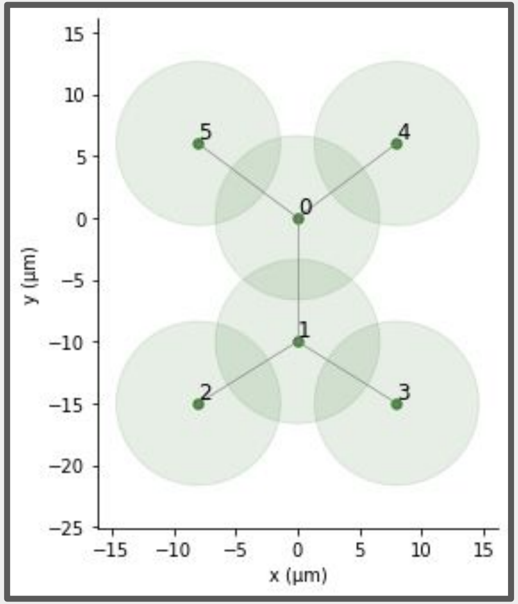
Time for the challenge !

Using the above physics, write a program that finds a minimal CDS of the follwing graph using Pulser.

In [1]:
```
import networkx as nx
G = nx.Graph()
G.add_edges_from([(0,1),(0,2),(0,3),(1,4),(1,5)])
nx.draw(G,pos=nx.spring_layout(G))
```

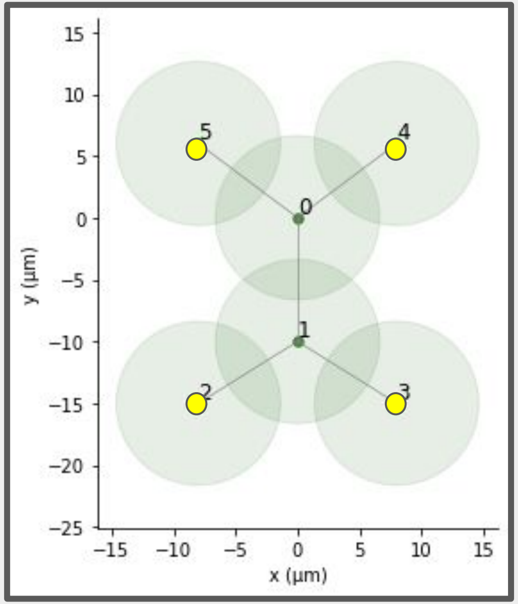


Map the sensors/graph to **neutral atom** coordinates



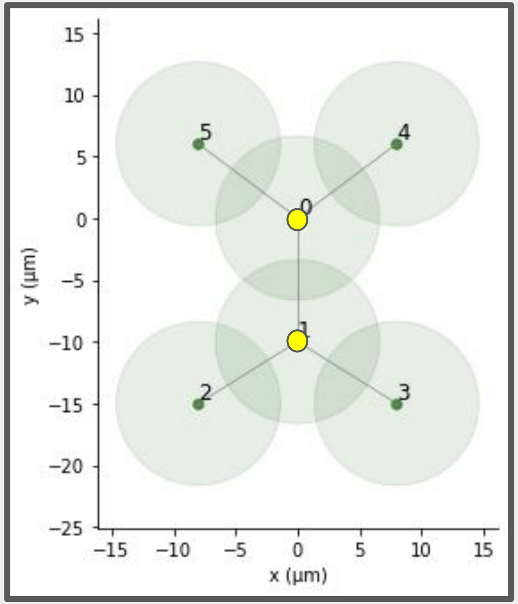
Our solution

Use **QAOA** and **Pulser** to find a **Maximally Independent Set (MIS)**



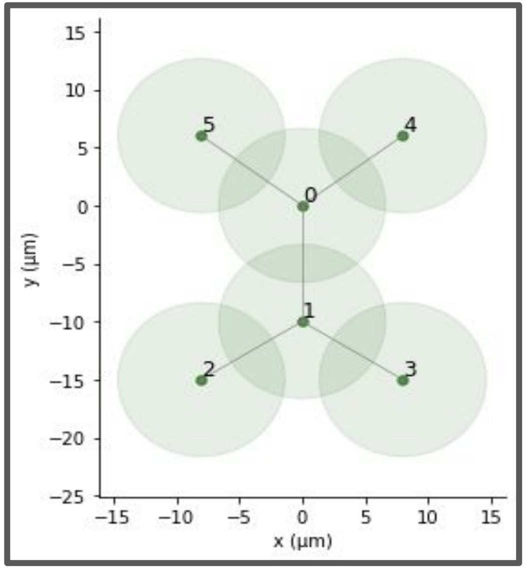
Our solution

Use the **MIS** solution to determine the **CDS**



Results

Encoded problem

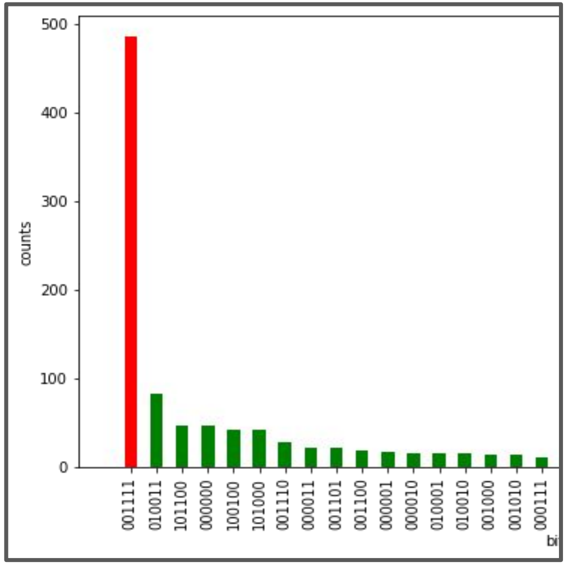


Hybrid quantum -classical optimization

MIS using **QAOA** and **Pulser**

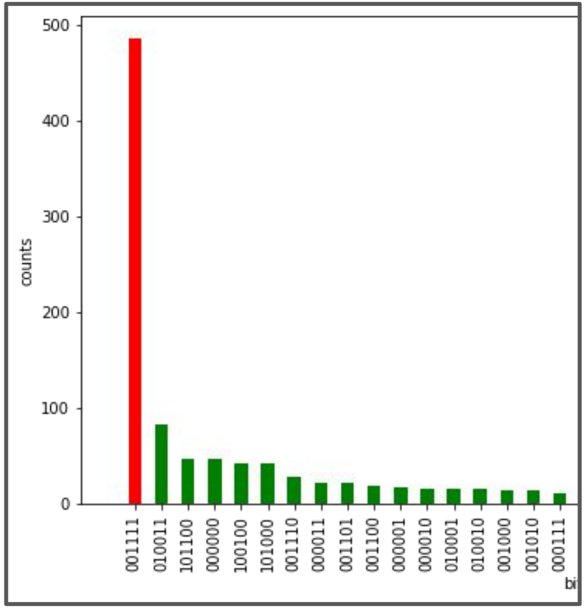
Fast parameter optimization using **Bayesian optimization**

MIS solution



Results

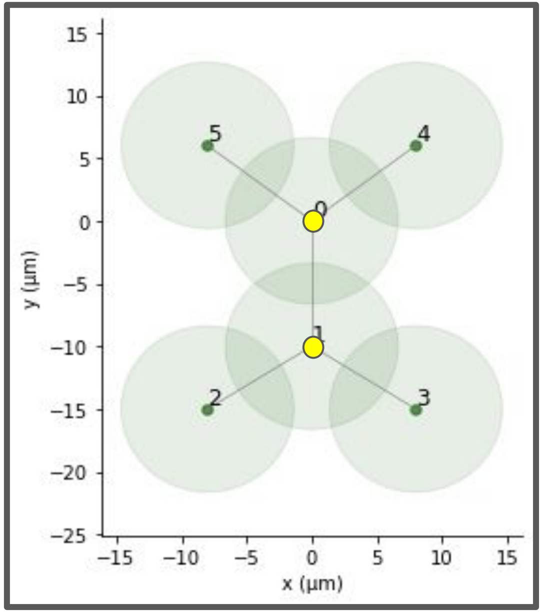
MIS solution



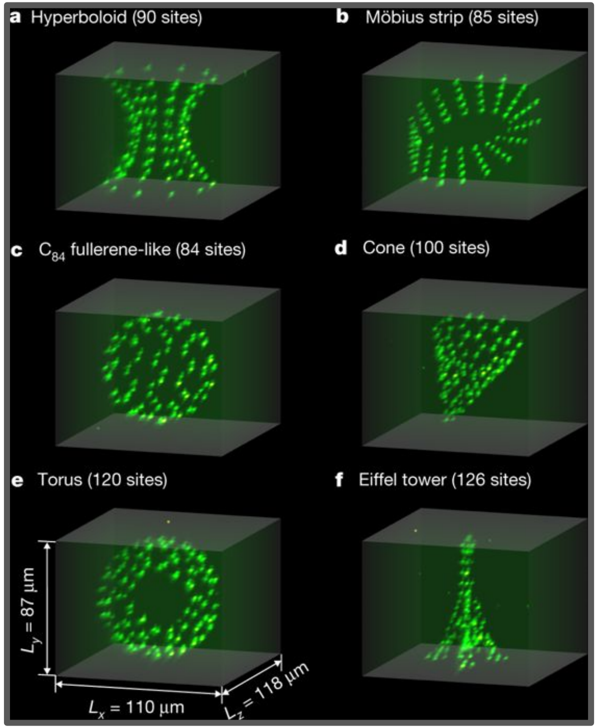
Classical post-processing

Iterative greedy search

CDS solution



Considerations for scalability



- Due to the **reconfigurable** nature of **neutral atom arrays**, our approach is scalable to the **number of neutral atoms** in a quantum computer
- We can easily extend our approach to **non-planar graphs** by using **3D neutral atom arrays**
- The iterative greedy algorithm to obtain a **CDS** from the **MIS** solution has a complexity of $\mathbf{O(n^2) \ll O(1.9407^n)}$

Quantum advantage

Finding the **MIS/CDS** of a graph is NP-hard : **$O(1.9407^n)$**

We **offload** the expensive computation to QPU and perform efficient optimization and post-processing classically

Neutral atoms are a natural platform for finding **MIS** and thus **CDS** to solve our use case

Summary

- **Our contribution :**
  - We developed a heuristic solution to find the **Connected Dominating Set** of a graph using **Neutral Atom Quantum Computing** and **Pulser**

- **Application to use-case :**
  - In a real-world scenario, we found that the **sensor positions** can be mapped to **neutral atom positions** and our approach can be used to find a **virtual backbone**

- **Quantum advantage :**
  - NP-hard problem to solve i.e. $O(1.9407^n)$ can be solved efficiently

Appendix

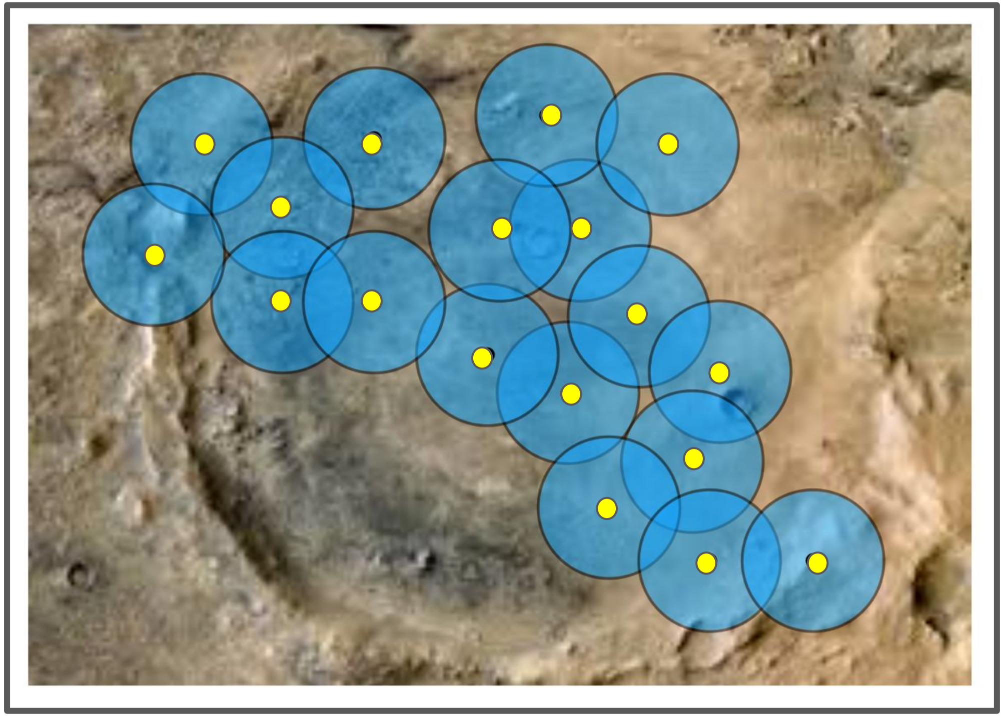
Thank you. Questions ?

Outline

1. Problem background
2. Connected Dominant Set (CDS)
3. Our solution
4. Considerations for scalability
5. Future outlook

MANETs on Mars : Problem

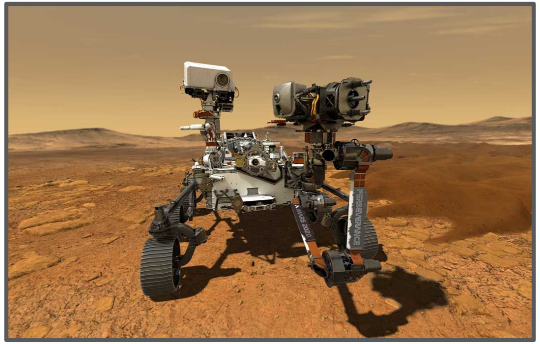
Global communication
guaranteed if all sensors are in transmit mode, but
- drains sensor battery
- redundant nodes spreading the same information

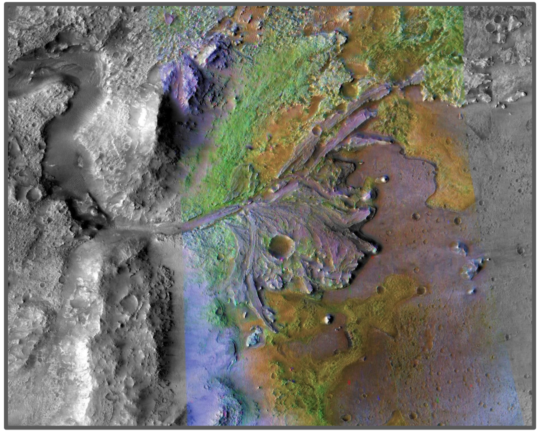


Must have in presentation

- Contribution on top of the existing use cases
    - QAOA for a new graph problem - did not find existing work
    - Implementation of the code on actual hardware
- Application to industry
    - In real-world scenario, the positions of the sensors has to be mapped to neutral atoms and the rydberg blockade radius set accordingly
- Quantum advantage
    - NP-hard problem to solve
    - Existing approach O(1.9407^n)

Perseverance on Mars





Finding **Martian** sources of water is crucial for human exploration of Mars

Perseverance landed in the **Jezero Crater** in February 2020 and searching for signs of microbial life under the surface

Curiosity landed in the **Gale Crater** in August 2012 and searching for signs of water and organic life

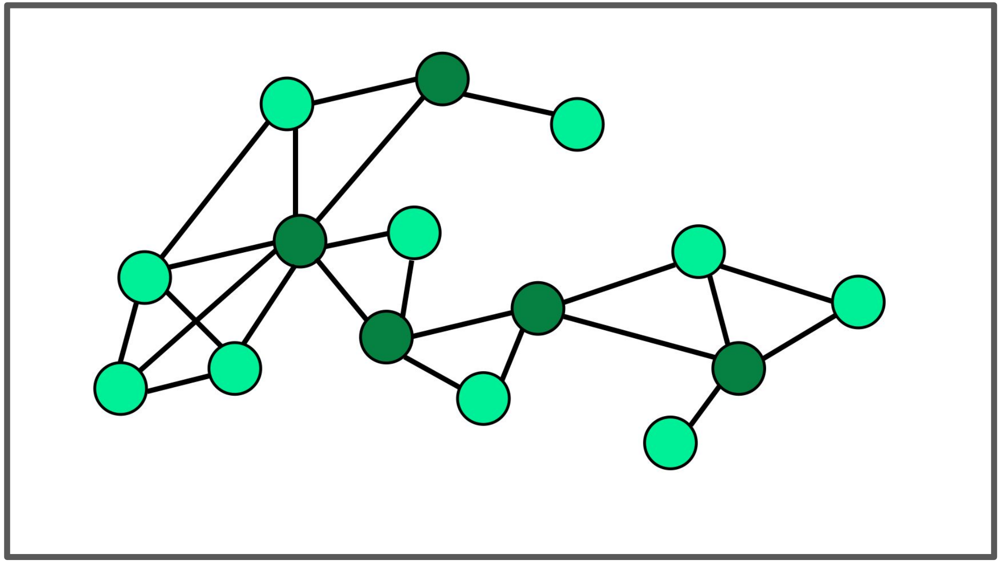
Problem : The area to search is large and progress is slow. For e.g. Perseverance has only explored a thin line of 11.76 km in 2 years.

Connected Dominant Set

Finding the CDS of a graph is NP-hard

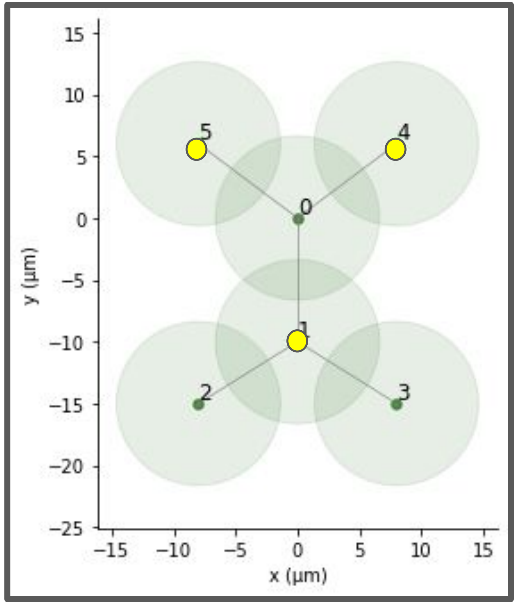
Best exact classical algorithm : **$O(1.9407^n)$**

Technical goal : Find a "good" CDS of a graph using the capabilities of neutral atoms and Pulser



QAOA

Maximally Independent Set (MIS)



Original cost function:

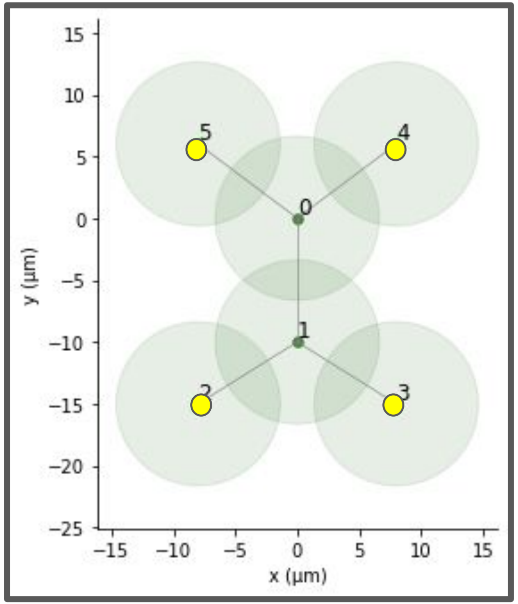
$$C(z_1, \ldots, z_N) = -\sum_{i=1}^{N}(z_i) + U\sum_{<i,j>} z_i z_j$$

Cost function with weighted nodes:

$$C(z_1, \ldots, z_N) = -\sum_{i=1}^{N}(\boxed{w_i} z_i) + U\sum_{<i,j>} z_i z_j$$

w_i = degree of the i^{th} node

Maximally Independent Set (MIS)

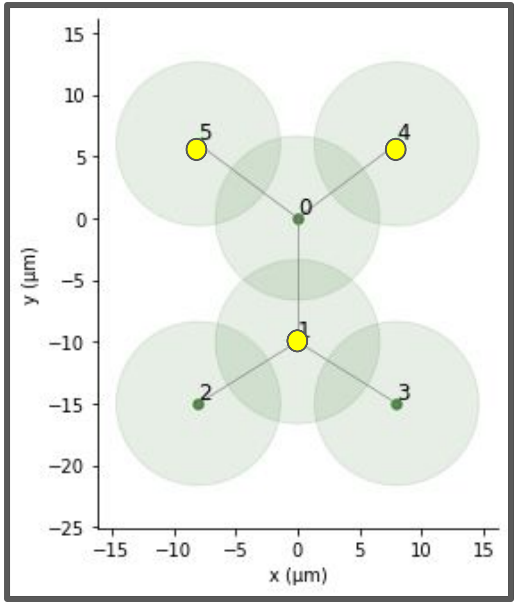


Graph **G** = (**V**, **E**)

Maximally Independent Set (**MIS**) is a subset **MIS** ⊂ **V** such that

- **None** of the vertices in **MIS** are connected
- Each node in **V/MIS** is a neighbor of at least one node in **MIS**

Maximally Independent Set (MIS)



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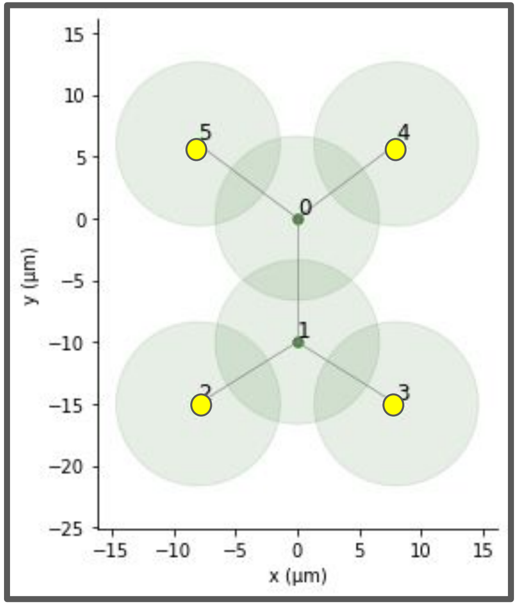
Maximally Independent Set (MIS)



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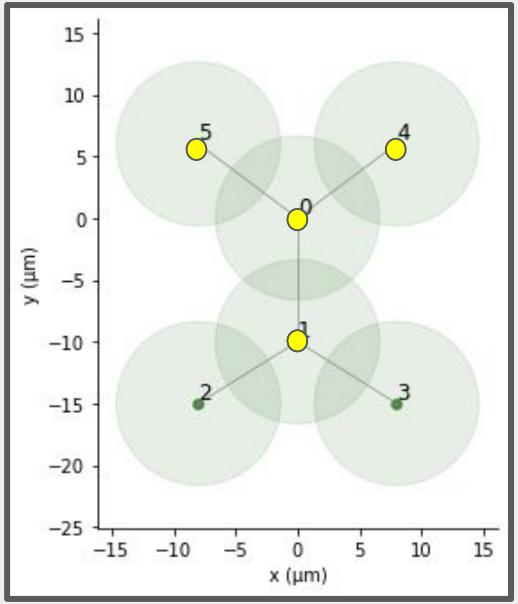
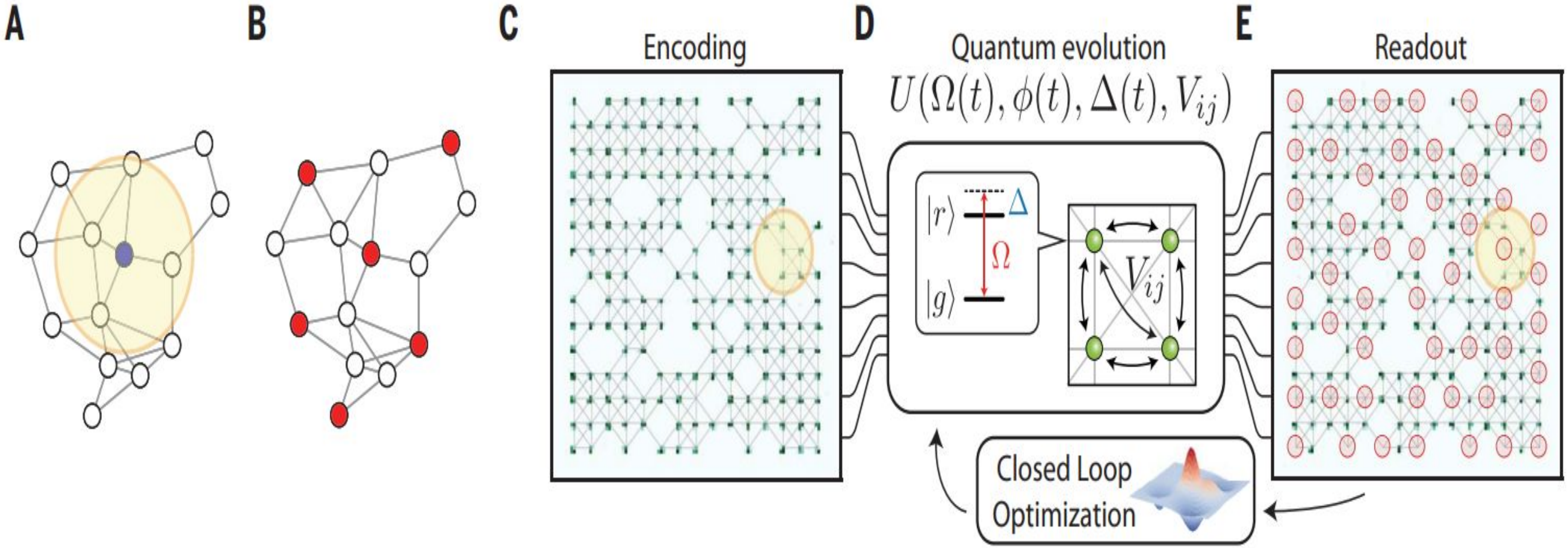
Iteratively add vertices to the **MIS** solution to obtain a **CDS**



QAOA



A
B
C
Encoding
D
Quantum evolution
$U(\Omega(t), \phi(t), \Delta(t), V_{ij})$
$|r\rangle$
Δ
Ω
$|g\rangle$
V_{ij}
E
Readout
Closed Loop
Optimization

Results