

GBS4EO: Gaussian Boson Sampling for Earth Observation

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Agenda

Motivation and problem

Gaussian Boson Sampling

Experimental setup

EO datasets and tasks

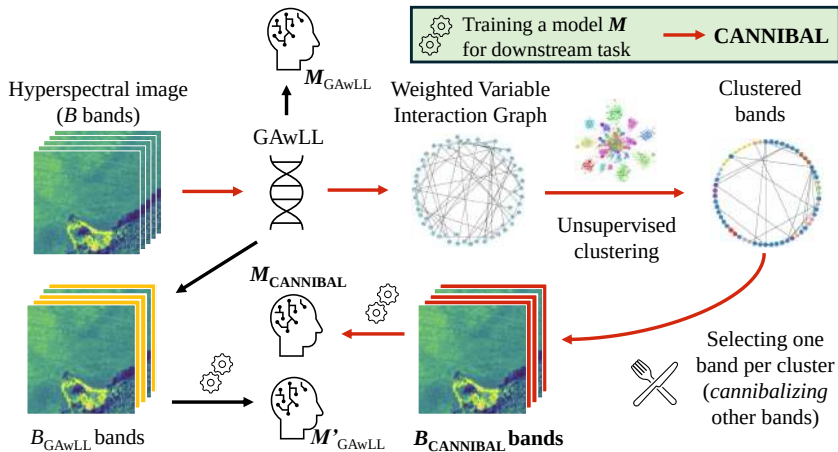
Motivation and problem



The problem

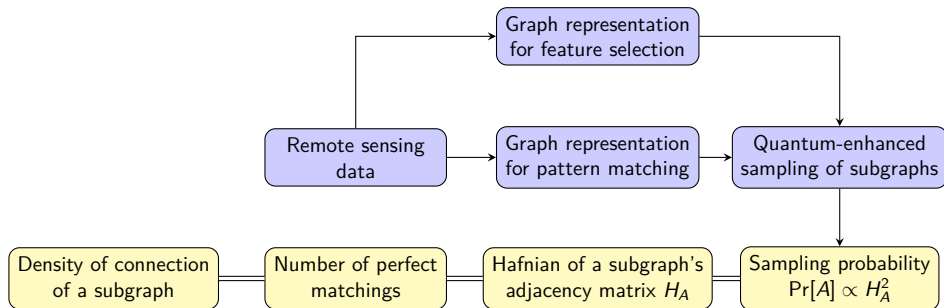
- ▶ I have been **sceptical** of quantum computing since 2001.
- ▶ I want to **disprove** my scepticism by finding a useful application.
- ▶ How can quantum computing help with **climate change adaptation** measures?
- ▶ We should investigate methane leaks — a powerful greenhouse gas.
- ▶ We focus on **band selection and pattern matching** in hyperspectral and multispectral images.

Baseline algorithm



Source: L. Tulczyjew, M. Przewozniczek, R. Tinós, A. M. Wijata, and J. Nalepa, "CANNIBAL unveils the hidden gems: hyperspectral band selection via clustering of weighted variable interaction graphs," in Proceedings of the Genetic and Evolutionary Computation Conference, Melbourne VIC Australia: ACM, July 2024, pp. 412–421. doi: 10.1145/3638529.3654203.

The idea behind solution



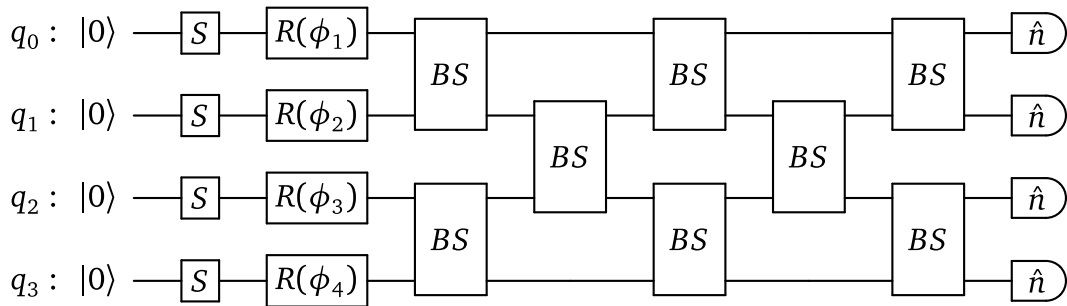
Overview of the solution

- ▶ Implementation of a quantum algorithm for finding dense sub-graphs in a graph.
- ▶ Application to clustering of the spectral bands into groups of similar bands.
- ▶ The logic of the algorithm:
 - ▶ calculate statistical similarity between every pair of bands;
 - ▶ create a dense graph representing similarity between bands;
 - ▶ find dense clusters in the graph;
 - ▶ select one band for each cluster as a representation of this cluster.

Gaussian Boson Sampling



Gaussian Boson Sampling (GBS)



Gaussian Boson Sampling for programmers

Hafnian of a matrix is difficult to compute

- ▶ Hafnian is a permanent-like quantity defined for a symmetric even-size $S \times S$ matrix as:

$$\text{Haf}(A) = \sum_{P \in \text{Part}_S^2} \prod_{\langle i,j \rangle \in P} A_{ij}$$

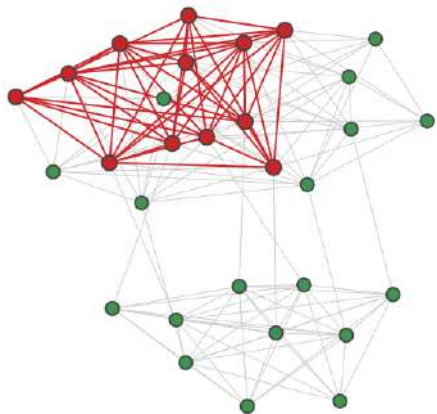
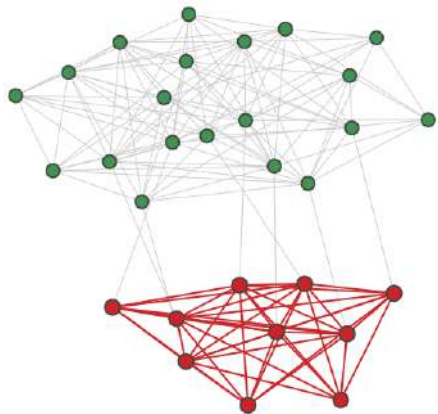
- ▶ Part_S^2 — partitions of set $\{1, \dots, S\}$ into disjoint pairs.
- ▶ **Crucial property:** Hafnian of an adjacency matrix of graph G equals to the number of **perfect matchings of the graph**.

Sampling dense subgraphs — main idea

GBS can be used to sample dense subgraphs of a given graph G [2].

- ▶ Dense subgraphs are those that have many edges.
- ▶ The entire idea works due to proven positive correlation between the number of perfect matchings and density of randomly sampled subgraphs [1].
- ▶ Assessing the number of perfect matchings of a randomly picked graph is computationally hard ($\#P$ -complete).
- ▶ Here comes GBS as a solution.

Samples of dense subgraphs



Clustering Algorithm — main loop

while(A “big enough”) **do**:

- ▶ $k := 0$;
- ▶ searchCluster := true;
- ▶ **while**(searchCluster) **do**:
 - ▶ sample N times $\{\vec{s}_{0,1}\} = \text{GBS}[M, A, \bar{n}]$;
 - ▶ postselect $\{\vec{s}_{0,1}\}_{S_{\min}}$ samples with at least $S_{\min}$ nodes;
 - ▶ choose $\vec{s}_{\max} \in \{\vec{s}_{0,1}\}_{S_{\min}}$ with highest number of edges n_{edge} ;
 - ▶ **if**($n_{\text{edge}} \geq \text{dens}[k]$):
 - ▶ $\text{Cl} := \text{Cl} + \vec{s}_{\max}$;
 - ▶ searchCluster := false;
 - ▶ $k := k + 1$;
- ▶ remove subgraph $\vec{s}_{\max}$ identified as cluster from A ;
- ▶ update parameters $\bar{n}, S_{\min}$, which may depend on size of A ;

Experimental setup



Piquasso

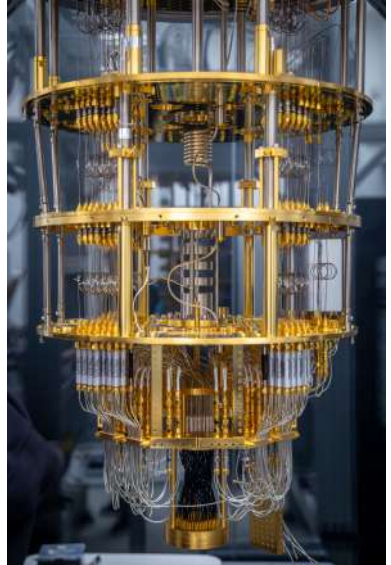
```
A = np.array(  
    [  
        [0, 1, 0, 1, 1],  
        [1, 0, 0, 0, 1],  
        [0, 0, 0, 1, 0],  
        [1, 0, 1, 0, 1],  
        [1, 1, 0, 1, 0],  
    ]  
)  
  
with pq.Program() as program:  
    pq.Q(all) | pq.Graph(A, mean_photon_number=1.0)  
    pq.Q(all) | pq.ParticleNumberMeasurement()  
  
simulator = pq.GaussianSimulator(d=len(A))  
result = simulator.execute(program, shots=shots)
```



PIQUASSO

VLQ — Quantum computer

- ▶ Produced and delivered by IQM
- ▶ 24 superconducting qubits with quantum resonator
- ▶ star topology
- ▶ located in Ostrava (CZ)
- ▶ operated by IT4I@VSB
- ▶ connected to HPC systems across Europe



Fock space to qubits compiler



- ▶ Approximation of Gaussian Boson Sampling using quantum gates
- ▶ Tests using VLQ
- ▶ What IF? (we had 1000 qubits)

EO datasets and tasks



Methane plumes

Space application

Detection of methane emitters (STARCOP)

AVIRIS-NG: 8 selected bands + methane concentration map

Data modality

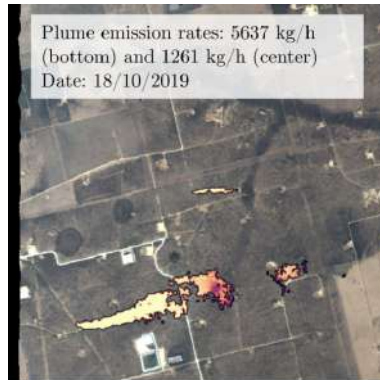
HSI 9 bands

Downstream task

Detection and localization of methane plumes

Pros

- ▶ An important and timely research topic on climate change
- ▶ A public dataset (STARCOP: <https://zenodo.org/records/7863343>) – will be used for pattern matching
- ▶ Lots of models (both classic machine learning and deep machine learning) for methane detection developed at KP Labs in various projects (including CHIME feasibility study, PINEAPPLE, FAST-EO)



Hyperspectral unmixing

Space application

Hyperspectral unmixing — multi-target regression
six end-members (Urban benchmark)

Data modality

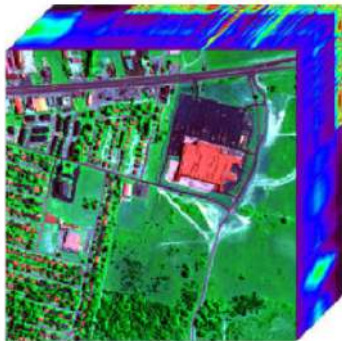
HSI 162 bands

Downstream task

Hyperspectral unmixing

Pros

- ▶ Direct comparison with our algorithm, CANNIBAL (clustering of weighted variable interaction graphs, ACM GECCO 2024)
- ▶ Rather a “toy” dataset (might not be very appreciated as a single dataset in experiments by the EO community, but should not be an issue when coupled with HYPERVIEW2)



Hyperspectral segmentation

Space application

Hyperspectral segmentation (pixel-level classification)/classification
nine classes (Pavia University)

Data modality

HSI 103 bands

Downstream task

Image segmentation, image classification

Pros

- ▶ Direct comparison with our algorithm, CANNIBAL (clustering of weighted variable interaction graphs, ACM GECCO 2024)
- ▶ Rather a “toy” dataset (might not be very appreciated as a single dataset in experiments by the EO community, but should not be an issue when coupled with HYPERVIEW2)



Hyperview2

Objective

To advance the state of the art of AI models for [soil parameter retrieval](#)

- ▶ airborne hyperspectral images,
- ▶ Sentinel-2 multispectral satellite images and
- ▶ PRISMA hyperspectral satellite images.

Task

To develop an [explainable AI](#) model to estimate the concentration of soil contaminants/trace elements:

- ▶ Boron (B),
- ▶ Copper (Cu),
- ▶ Zinc (Zn),
- ▶ Iron (Fe),
- ▶ Sulphur (S), and
- ▶ Manganese (Mn).

in top soil using Earth observation imagery

Make AI in space make sense

#HYPERVIEW2 // EASI // ECAI

<https://platform.s4eo.eu/hyperview2>

#HYPERVIEW2

AI4EO
Challenges

HP LABS

ESA ID-100



Thank You!



IT4INNOVATIONS
NÁRODNÍ SUPERPOČÍTAČOVÉ
CENTRUM

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