Evolution of SATCOM system architectures : Nano-satellite swarms

General introduction

Evelyne Akopyan, TéSA - Toulouse INP

09/01/2024

7 boulevard de la Gare – 31500 Toulouse – France
evelyne.akopyan@tesa.prd.fr

Presentation

- Master's degree in Telecommunications (INSA Lyon, 2020)
- Big Data research engineer (LICIT-CEREMA, 2020-2021)
- PhD in telecommunications (TéSA-CNES, 2021) : Resilient network architectures for nano-satellite swarms

Nano-satellites

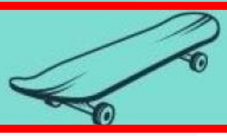
Classification, deployment and state of the art

What’s a nano-satellite?

- Miniaturized artificial satellite with a mass of 1 to 10 kg
- Main asset: limited production and launch costs

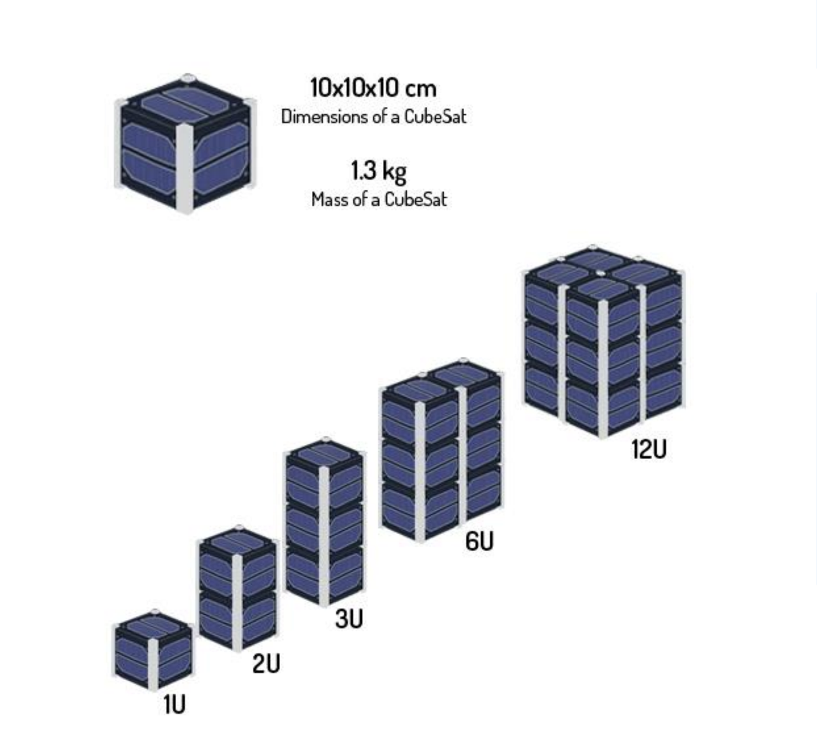
- State of the research on nano-satellite swarms: 8 papers in 2000, 300 in 2022 (Google Scholar references)
  - Satellite networks: > 6,000 papers
  - Covid-19 : > 60,000 papers

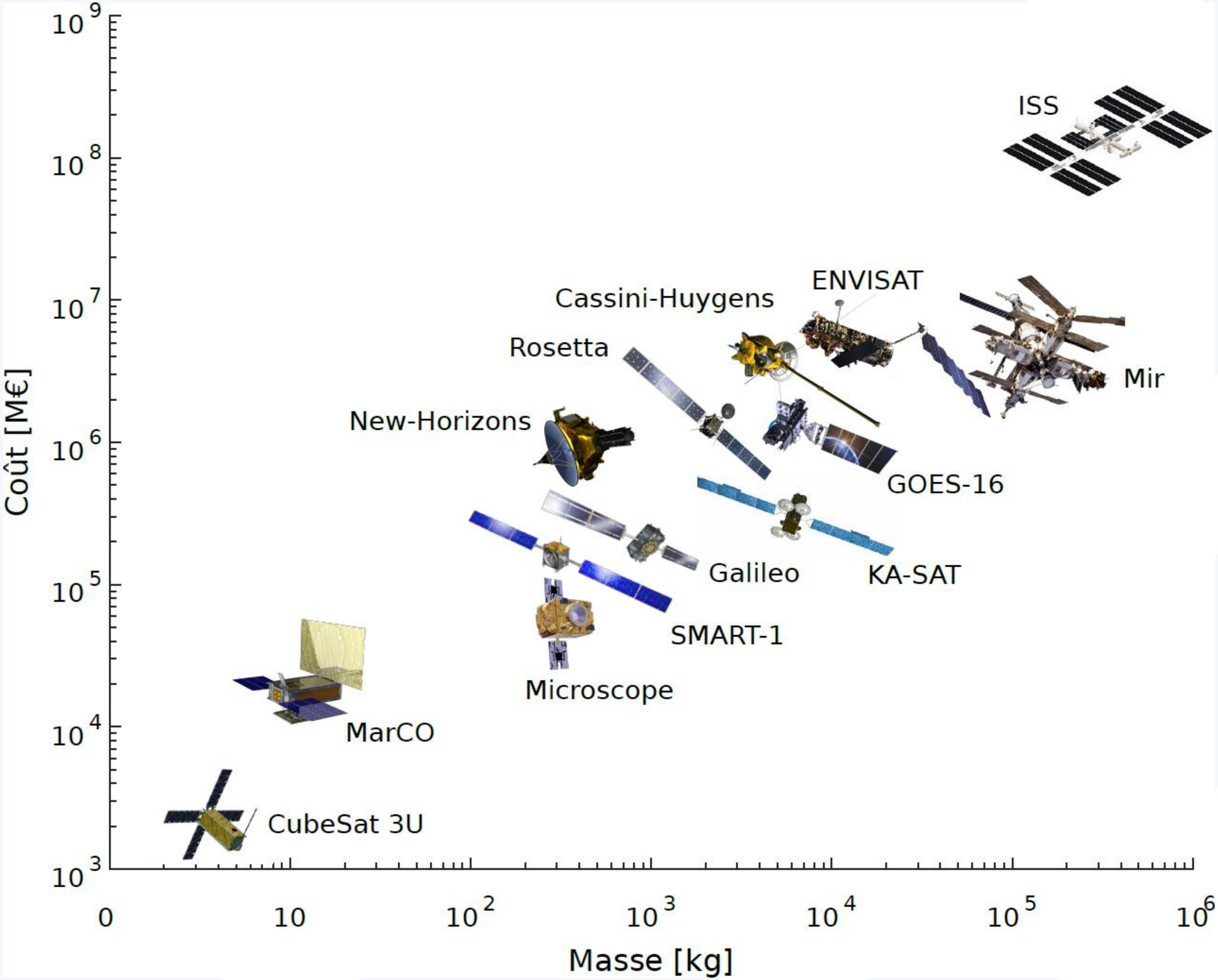
Classification

CATEGORY	WEIGHT	SIMILAR IN SIZE TO A …
LARGE	More than 1,000 kg	
MEDIUM	500-1,000 kg	
MINI	100-500 kg	
MICRO	10-100 kg	
NANO	1-10 kg	

Nano-satellite format

- CubeSat: nano-satellite format defined by a standard unit (1Unit, or 1U)
  - Usually a 10-cm cube





Coût [M€]
Masse [kg]
10^9
10^8
10^7
10^6
10^5
10^4
10^3
0
10
10^2
10^3
10^4
10^5
10^6
ISS
ENVISAT
Cassini-Huygens
Rosetta
Mir
New-Horizons
GOES-16
Galileo
KA-SAT
SMART-1
Microscope
MarCO
CubeSat 3U

Flight formations

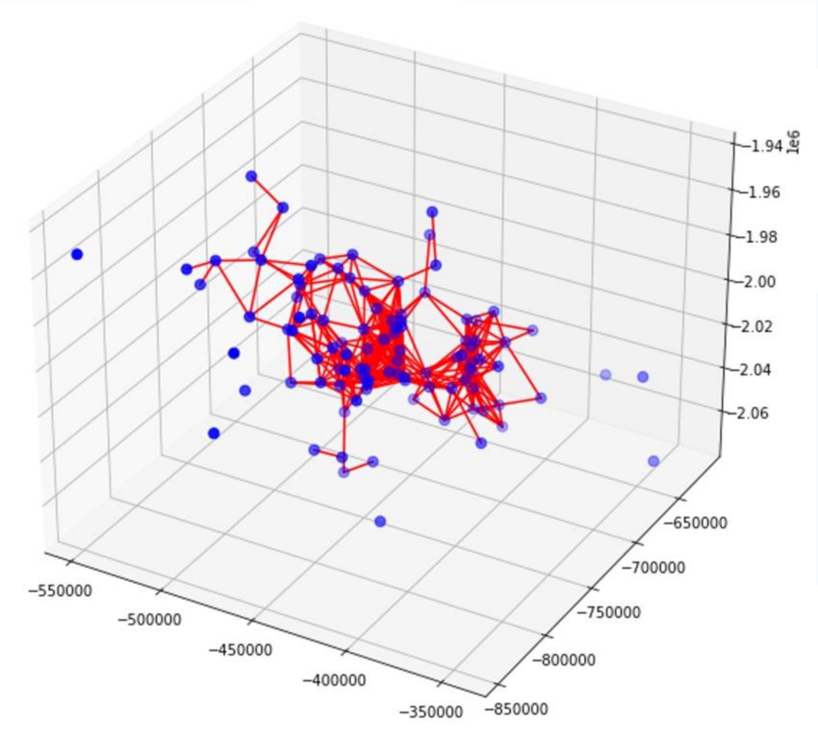
- **Constellation** : group of synchronized satellites which coverage areas on ground are complementary, providing a stable service (geolocalization, Internet access)

- **Trailing** : group of satellites orbiting the same path and separated by specific lapses, allowing to observe temporal evolutions (meteorology, ground mapping)

- **Cluster** : high-density group of satellites, providing high definition services (interferometry)

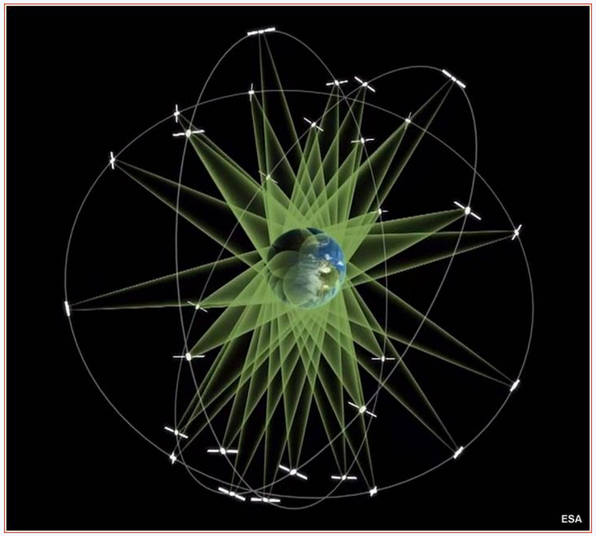
The swarm formation

- Derived from the cluster flight formation
- All satellites are on very close but distinct orbits
- Satellite positions are not fixed: desorganized aspect

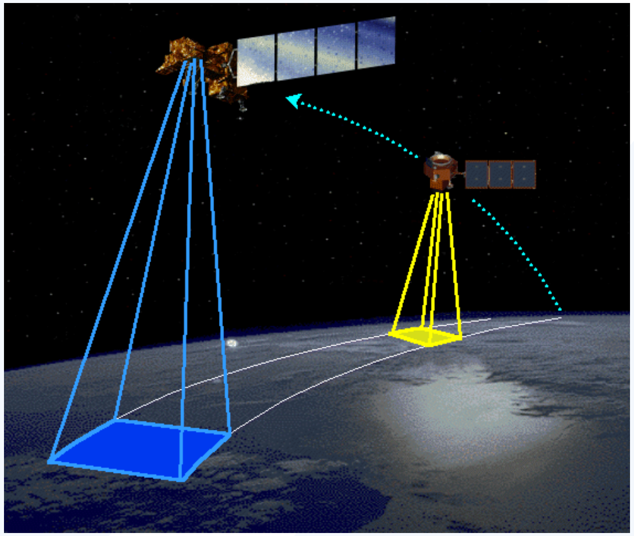


Simulation of a nano-satellite swarm

Examples of formations



Constellation: Galileo



Trailing: Landsat-7 and EO-1

?

Cluster/swarm

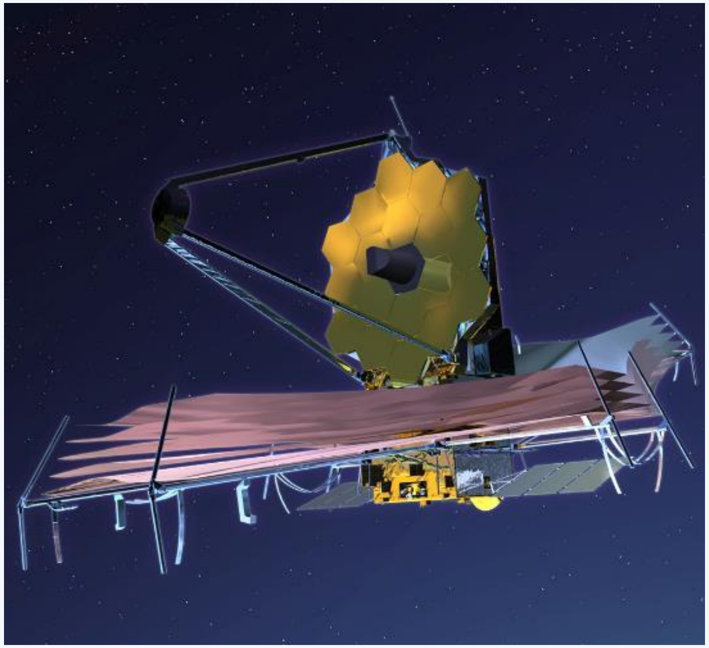
Swarms in nature

The interest of nano-satellite swarms

- Low-cost deployment of many basic nano-satellites to perform the task of a high-cost large satellite
- Opportunity to replace ground-based telescopes by spatial distributed telescopes
- Improvement of the robustness and resilience of the mission

Application example

Deep space observation



James Webb ▲

Hubble ▼

ALMA interferometer, Atacama ▲

Antennae galaxies

Composition of ALMA (low frequencies) and Hubble (visible light) signal observations

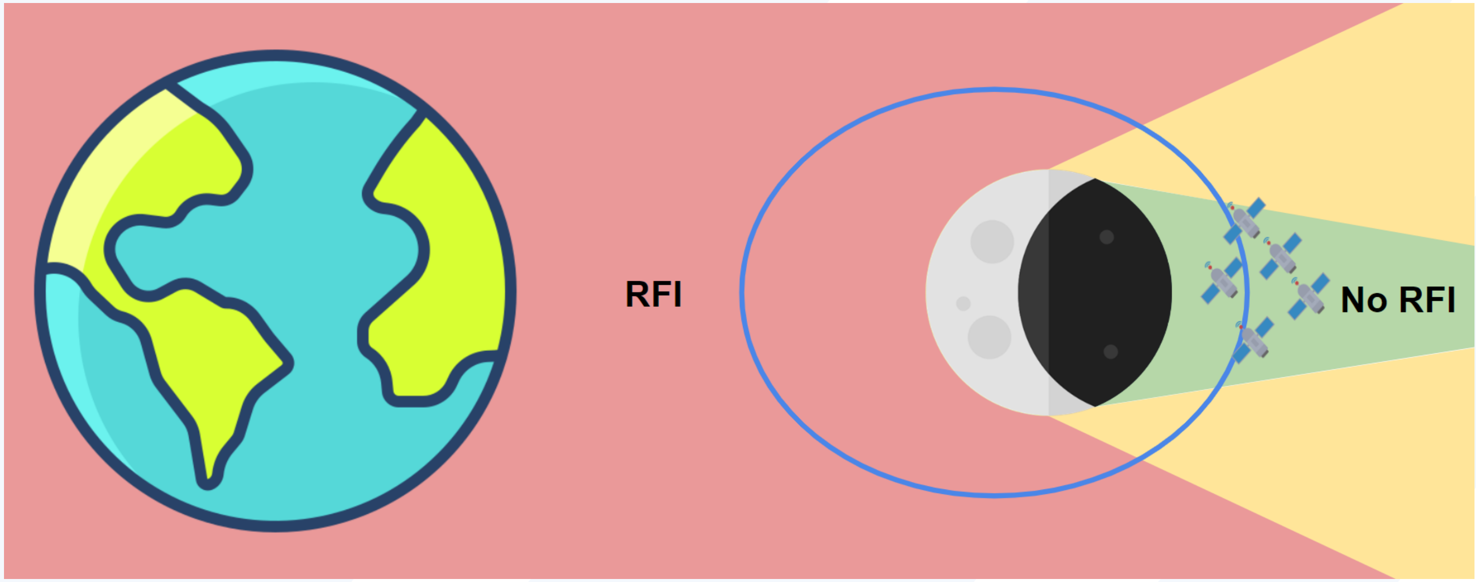
Interest of interferometry

- Analyzed frequencies: <100 MHz
  - Sky and (deep) space mapping
  - Observation of Dark Ages signals
- Current instruments: ground-based telescopes (antennae arrays)
- Sources of errors:
  - Ionospheric distortion
  - Terrrestrial radio frequency interferences (RFI)

VLA, New Mexique (USA)

Objective of the mission

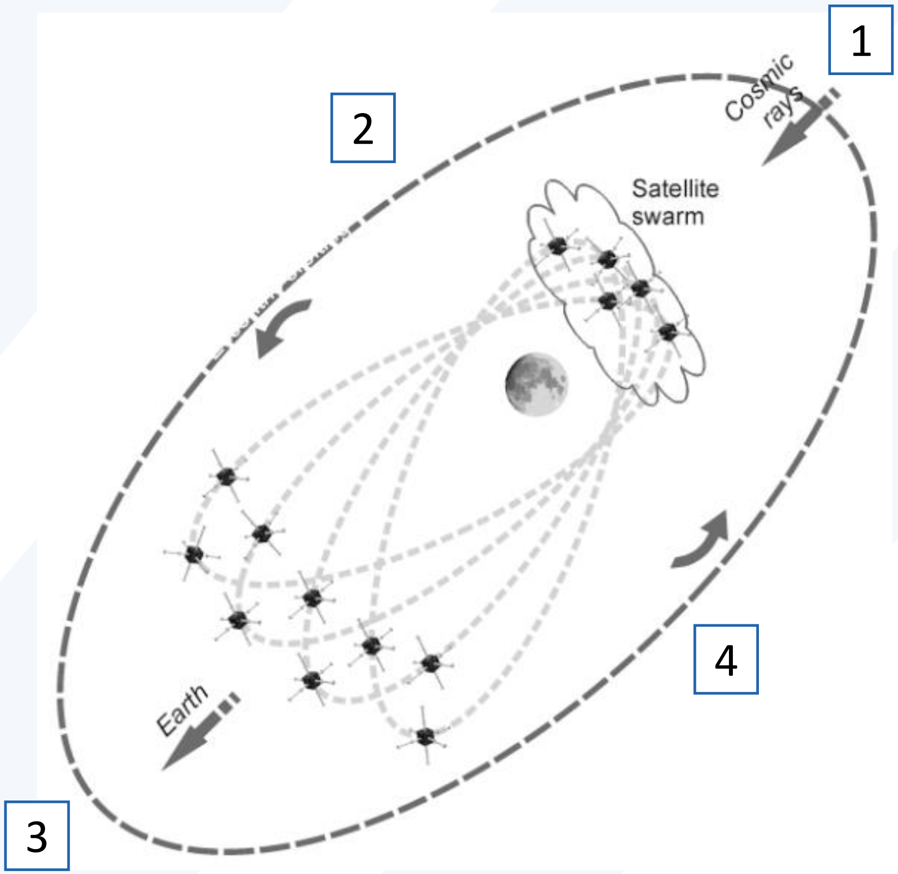
- Launch a swarm of 50 to 100 nano-satellites in orbit around the Moon
  - No ionosphere!
  - Natural protection against RFI



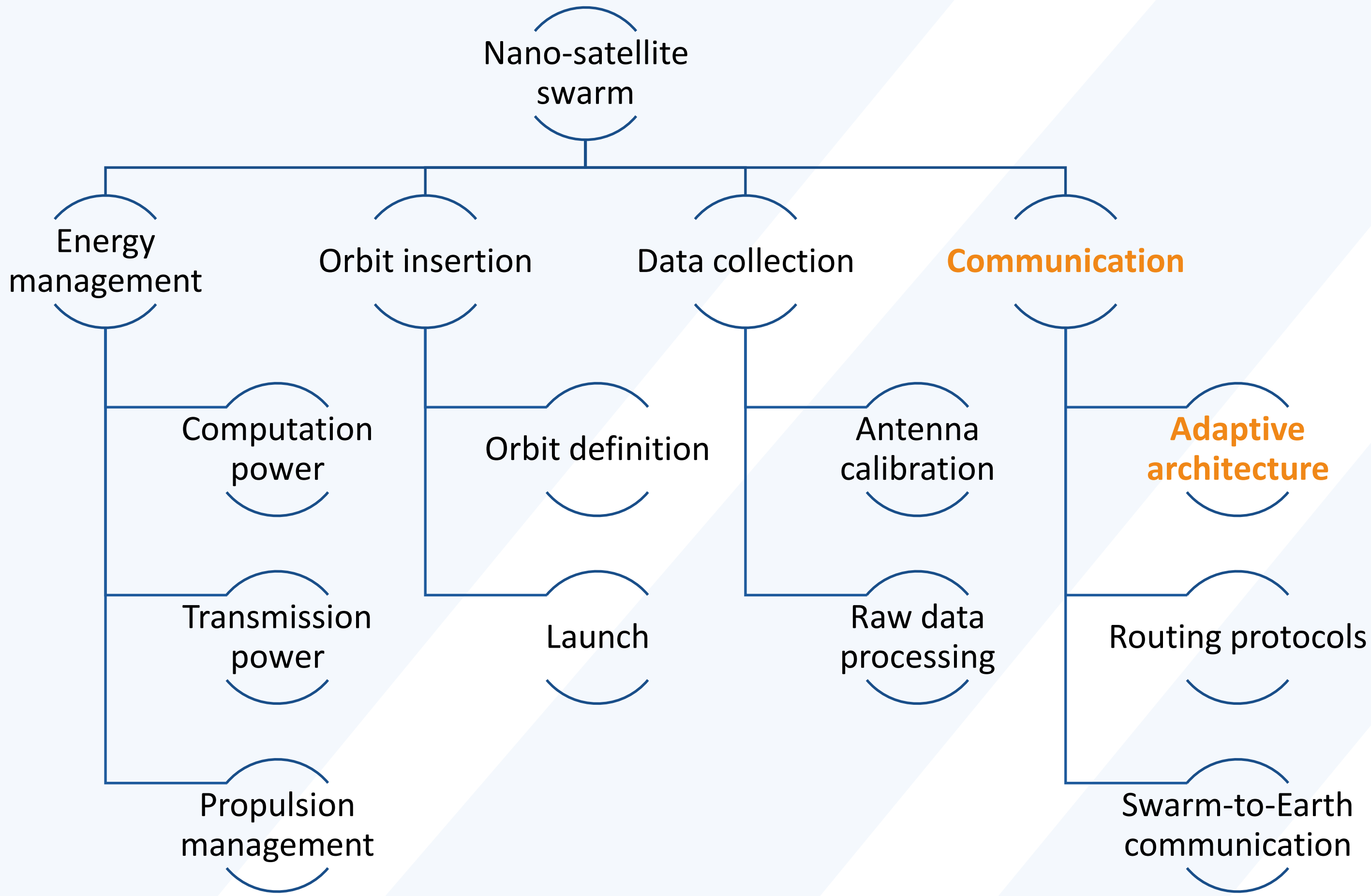
Creation of a distributed space radiotelescope

Operating mode

1. Space data sampling (60 to 600 Mb/s)
2. Data transfer and image computation
3. Transmission of the image back to Earth
4. Idle phase or re-organization



Non-exhaustive list of constraints



Communication constraints

The connectivity within the swarm is exclusively based on Inter-Satellite Links (ISL).

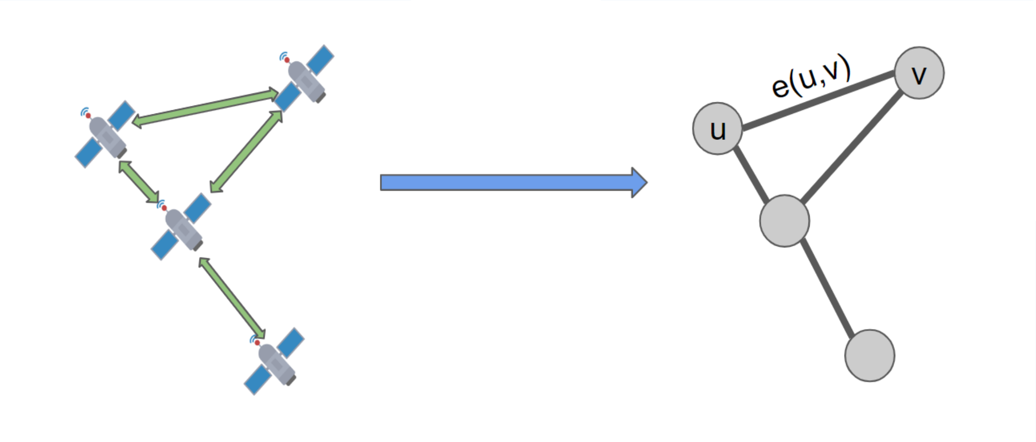
- Velocity of the satellites (1 to 10 km/s)
- Inter-satellite distance (approx. 30 km)
- No geolocalisation
- Amount of data for transmission (approx. 5 Gbits/sat)
  - Collisions
  - Packet losses
  - Congestion
- Zero experimental data!

Network properties

A graph theory-based approach

System description

- Swarm of 50 or 100 identical nanosatellites
- Omnidirectionnal antennae for communication
- Pseudo-periodic trajectory of the swarm around the Moon
- Intra-swarm mobility
- Peer localization based on inter-satellite distances



Connection hypotheses

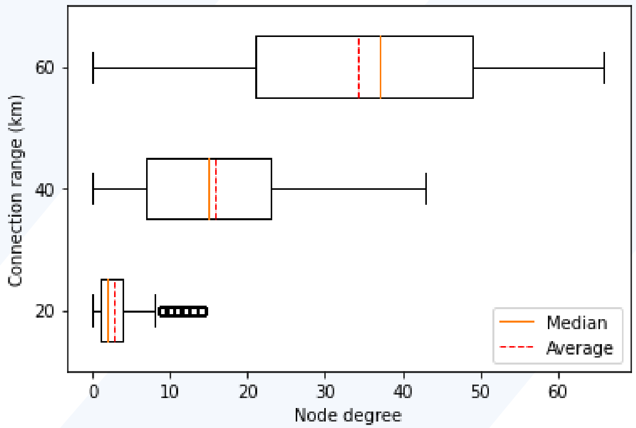
Two satellites can communicate if and only if there exists an ISL between them, i.e. they are in each other's **connection range**.

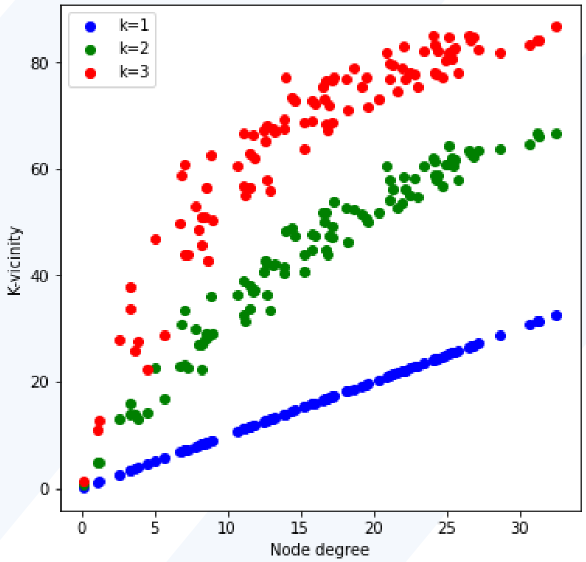
- Each ISL is a duplex link
- The connection range is identical for all satellites (30 km)
- All data packets are identical in size (5 Gbits)
- All packets are broadcasted
- There is no packet loss (bold assumption)

Swarm connectivity

- Study of the dynamics of the node neighborhood
  - Direct (degree)
  - Extended (k-vicinity)

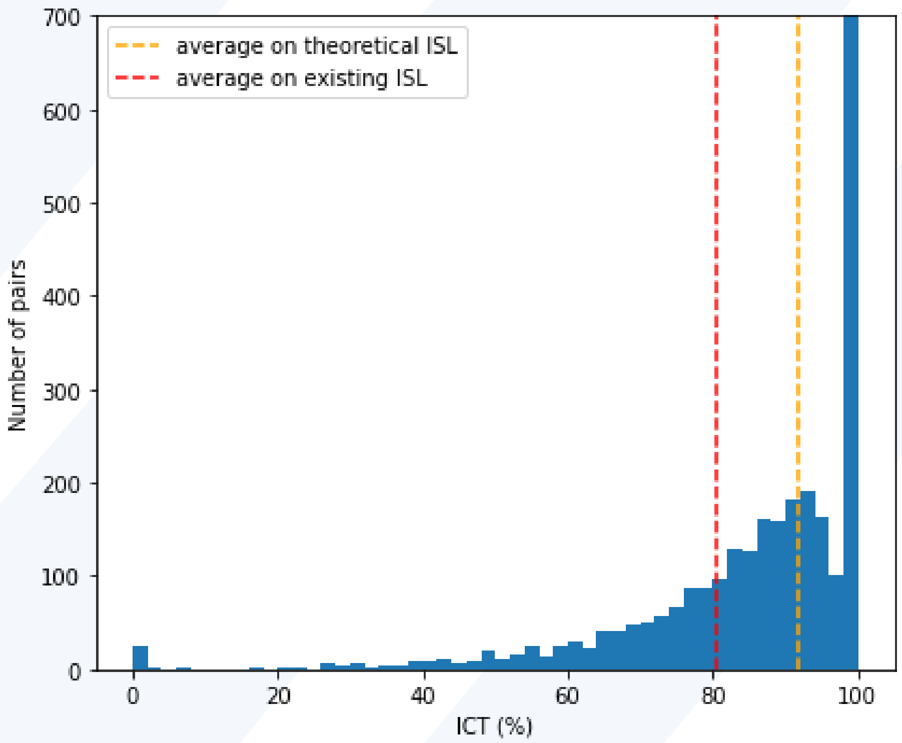
- Heterogeneous neighbor distribution: presence of high- and low-density zones





ISL disponibility

- Inter-Contact Time (ICT) : timelapse between successive connections on a given ISL
  - 0% ICT: permanent disponibility of the ISL
  - 100% ICT: no direct contact between the nodes
  - Average on all ISL: 80% ICT



Conclusions on swarm properties

- Heterogeneous connectivity: high- and low-density zones coexist, but the variation in node density is periodic.

- Heterogeneous disponibility: there exists a backbone of permanently connected pairs of nodes. The presence of such backbone implies that these nodes will consume more energy than the rest and thus go down faster.

An adaptive architecture is required to tackle strong heterogeneity.

Network overload control

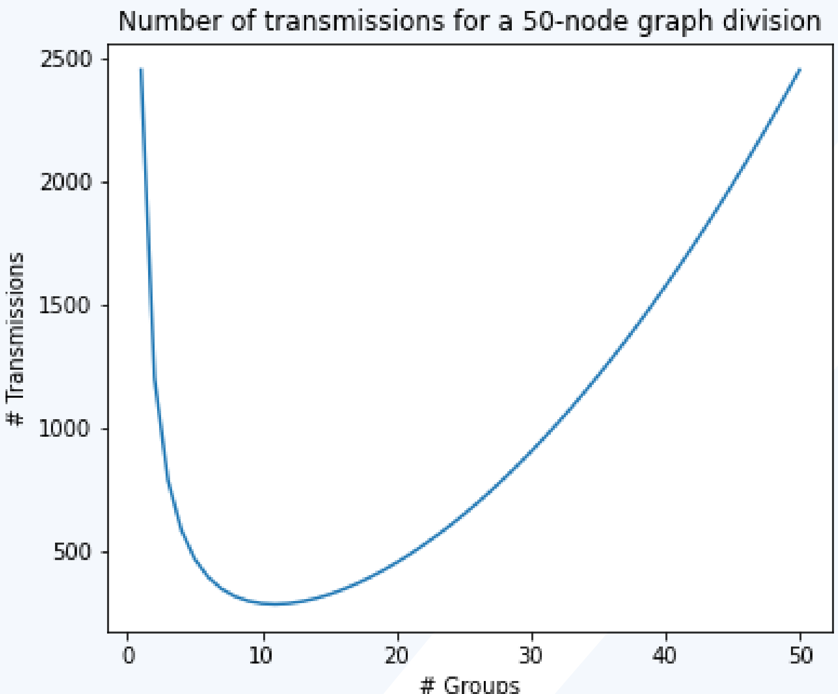
Trade-off between data redundancy and network efficiency

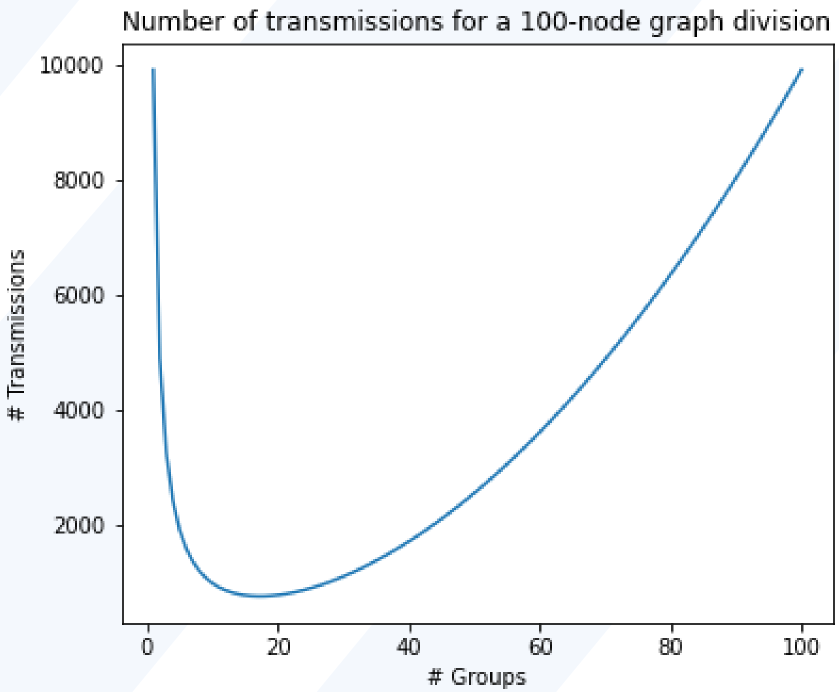
Problem definition

- Consider a swarm of N nodes ($N = 100$)
- Each node receives $N - 1$ data packets from the other nodes, and shares its own data packet with the other $N - 1$ nodes
- Each node computes the cross-correlated space image from these data packets
- The same image is computed N times, which is extremely redundant, but unsustainable in terms of network load!

Network load estimation

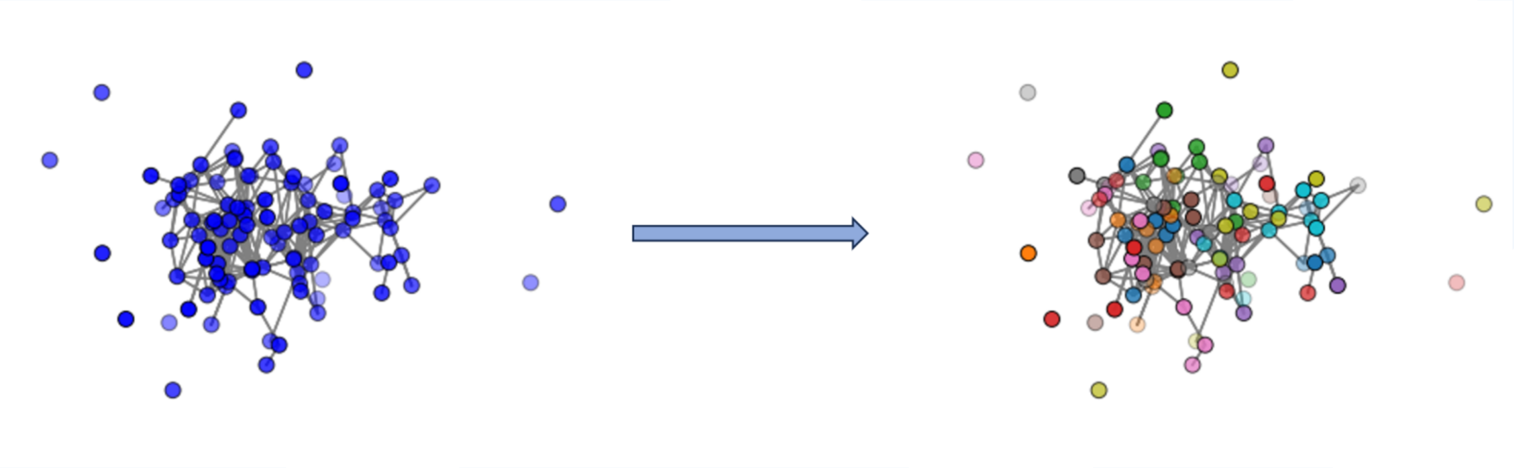
- What if we divide the network into groups?
- Number of packets to transmit = number of intra-group transmissions + number of inter-group transmissions





Proposed solution

- Compute the image x times ($x < N$), by sharing less data packets
- Fair network division: split the swarm into x groups that are similar to the original swarm in terms of network properties
  - ➢ Share the data within each group, then between each group



Why not clustering?

Technique	Clustering	Fair Division
Objective	Regroup similar nodes together	Divide the graph into groups that are similar to the original
Similarity metrics	Average degree, clustering coefficient, graph density, group size, diameter…	
Pros	Nodes of the same group are homogeneous	Groups are fair with each other
Cons	Groups are not fair with each other	Groups are not necessarily connected

To conclude…

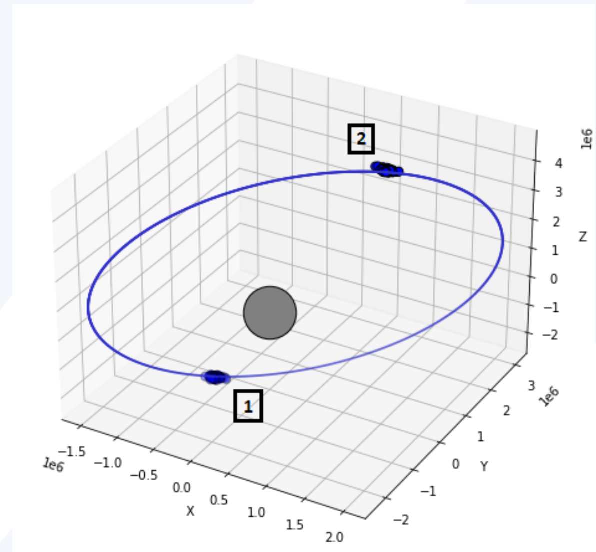
- Nano-satellite swarms: highly heterogeneous mobile distributed systems
- Implement an adaptive architecture to tackle the heterogeneity of the system
- Trade-off between packet redundancy and network efficiency
  - Packet overload management: fair network division

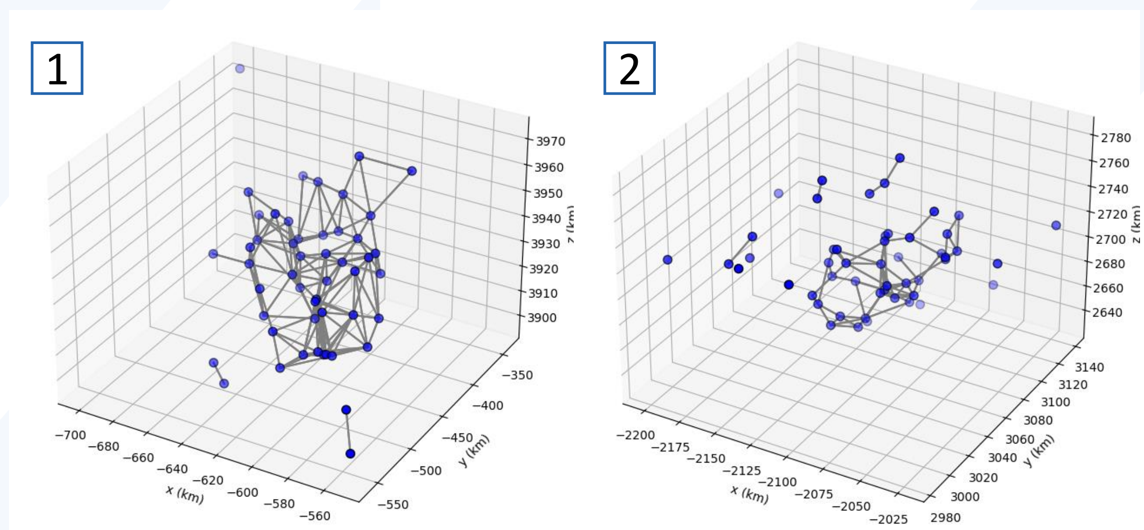
Useful information for the TP

Dataset description, metrics definition, a quick introduction to the simulation tool, etc.

Simulation tool

- Homemade Python3 module: **swarm_sim**
- Definition of Swarm and Node classes
- Basic operations on nodes
- Metrics computation
- Visualization…





Dataset description

Data are generated synthetically and follow Kepler's laws in space.

- 50 nano-satellite tracks:
  - Moon-centered (x,y,z) coordinate system, either fixed (F) or inertial (I)
  - Positions sampled every 10 seconds
  - Sampling duration: 24 hours (8641 samples)

- Revolution period of the swarm: 5 hours (1800 samples)

Fairness metrics definition

- **Average Degree (AD)** : average number of neighbors per node in a (sub)graph
- **Average Clustering Coefficient (ACC)** : for each node, the ratio between the observed number of edges between its neighbors and the maximum possible number of such edges, averaged on the (sub)graph
- **Graph Density (GD)** : ratio between the observed number of edges and the maximum possible number of edges in the (sub)graph
- **Sample size (N_i)** : number of nodes in the (sub)graph
- **Diameter (Dia)** : longest shortest path between all pairs of nodes in the (sub)graph