Nanosatellite Swarms

A quick introduction

Evelyne Akopyan, TéSA - Toulouse INP

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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 architecture for nanosatellite swarms

Nanosatellites

Classification, deployment and state of the art

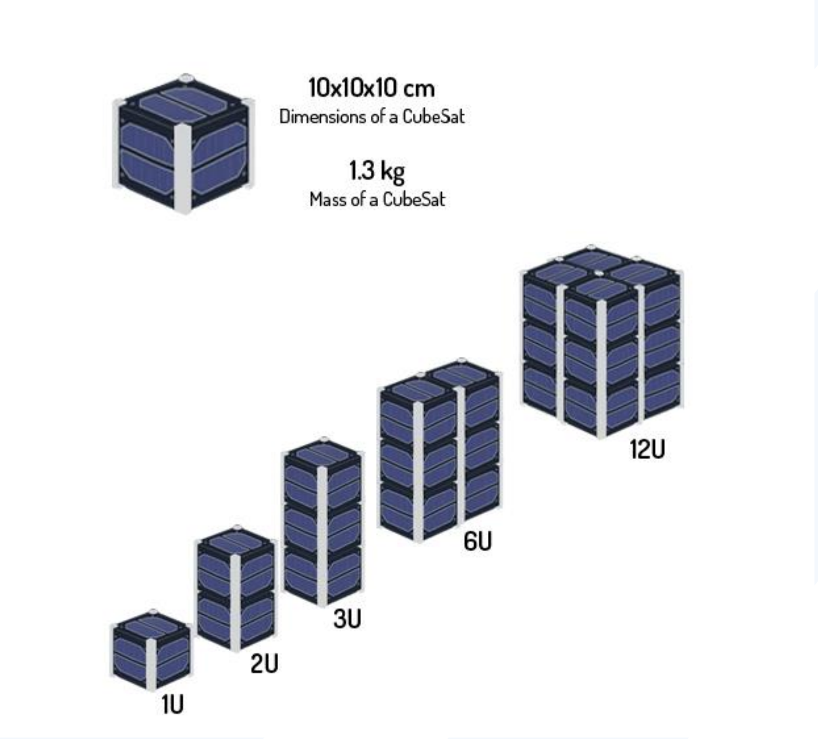
What is a nanosatellite ?

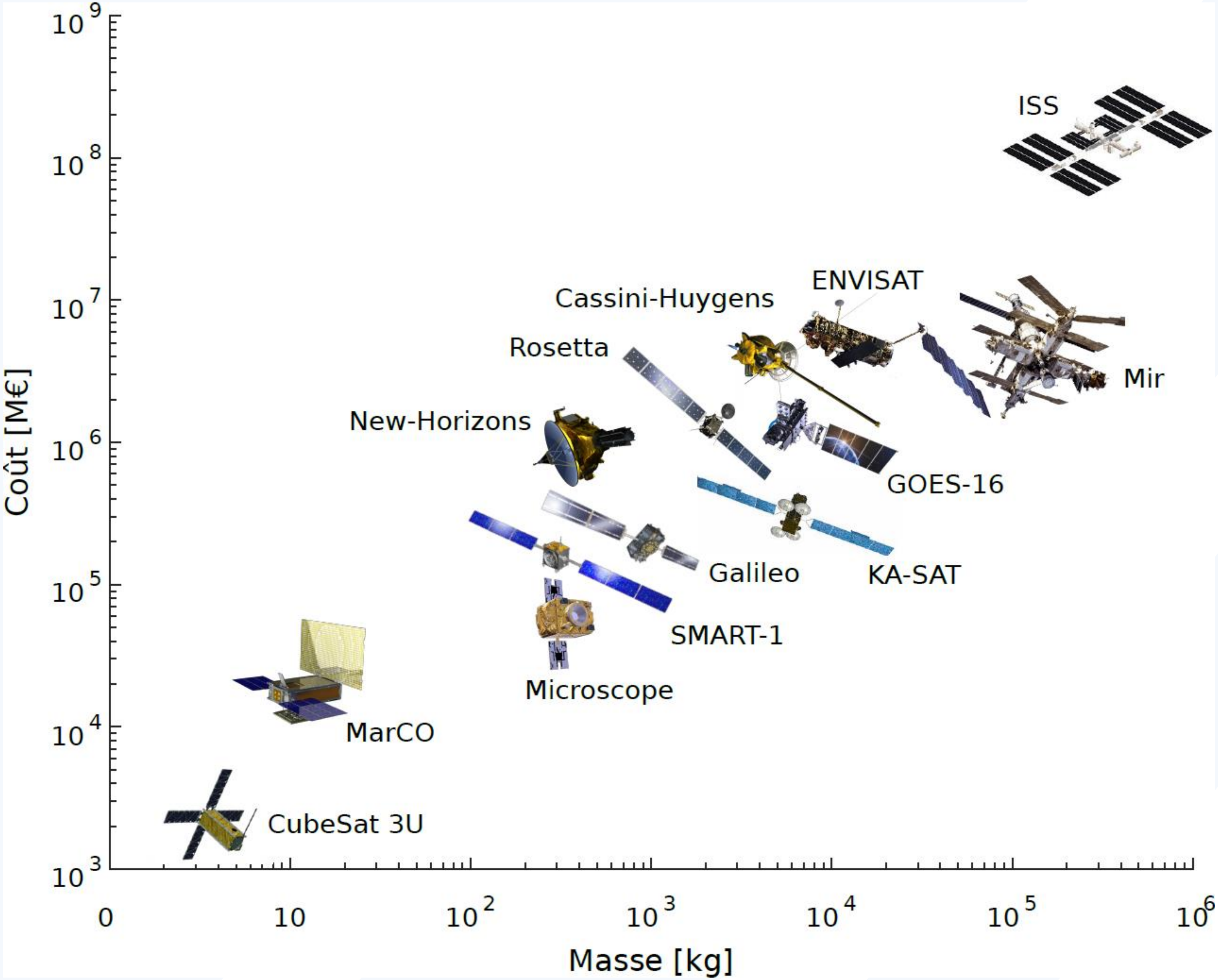
- Miniaturized artificial satellite with a mass of 1 to 10 kg
- Main asset: limited production and launch costs

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

Nanosatellite format

- CubeSat : nanosatellites format defined by a standard unit (1Unit, or 1U)
  - Generally a 10 cm cube





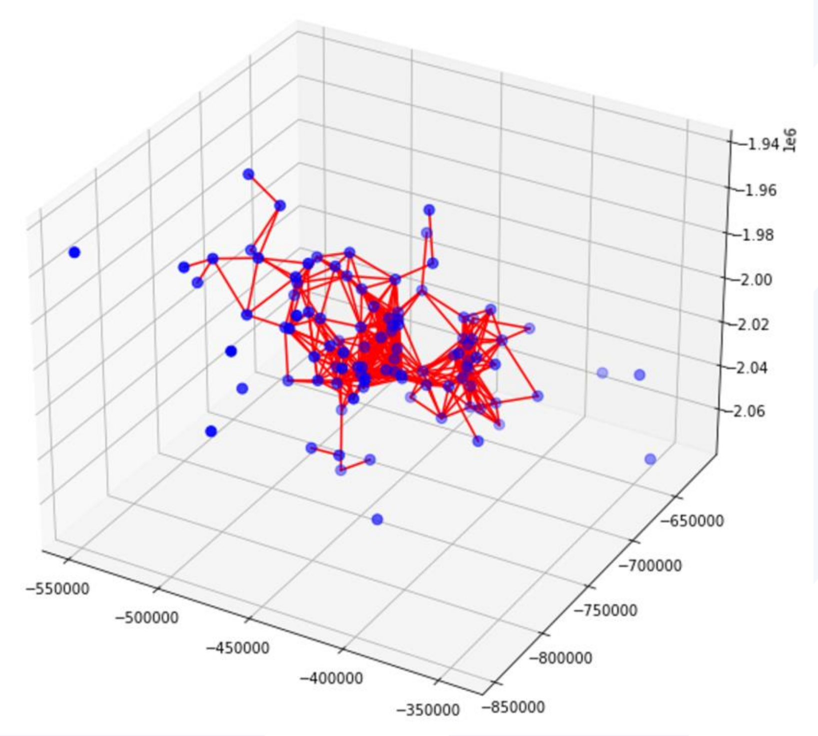
Coût [M€]
Masse [kg]
10^9
10^8
10^7
10^6
10^5
10^4
10^3
0
10
10^2
10^3
10^4
10^5
10^6
ISS
ENVISAT
Cassini-Huygens
Rosetta
Mir
New-Horizons
GOES-16
Galileo
KA-SAT
SMART-1
Microscope
MarCO
CubeSat 3U

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)

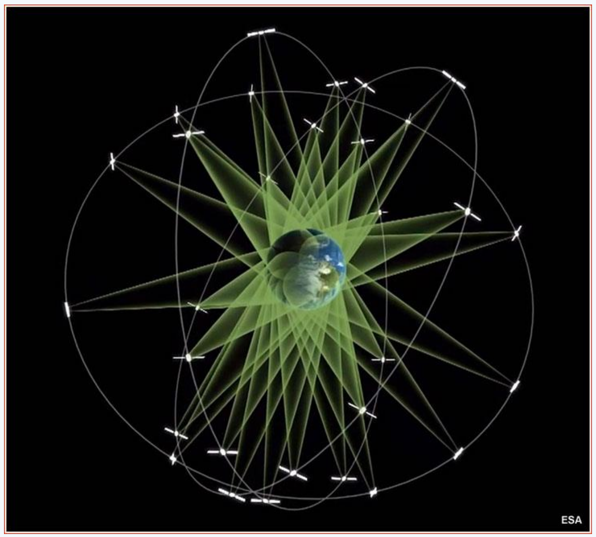
The swarm formation

- Derived from the cluster formation
- All satellites are on very close yet distinct orbits
- Positions are not fixed: desorganized aspect

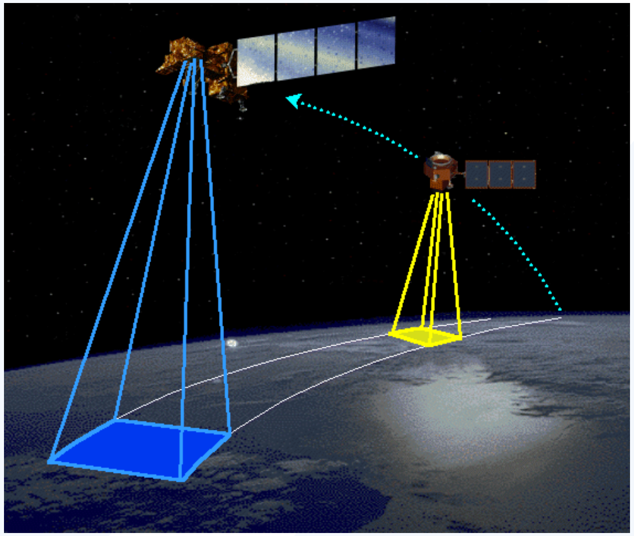


Simulation of a satellite swarm

Examples of formations



Constellation: Galileo



Trailing: Landsat-7 and EO-1

?

Cluster/swarm

Swarms in nature

The interest of nanosatellite swarms

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

Low-frequency radio interferometry

An example of application

Interest of interferometry

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

VLA, New Mexico (USA)

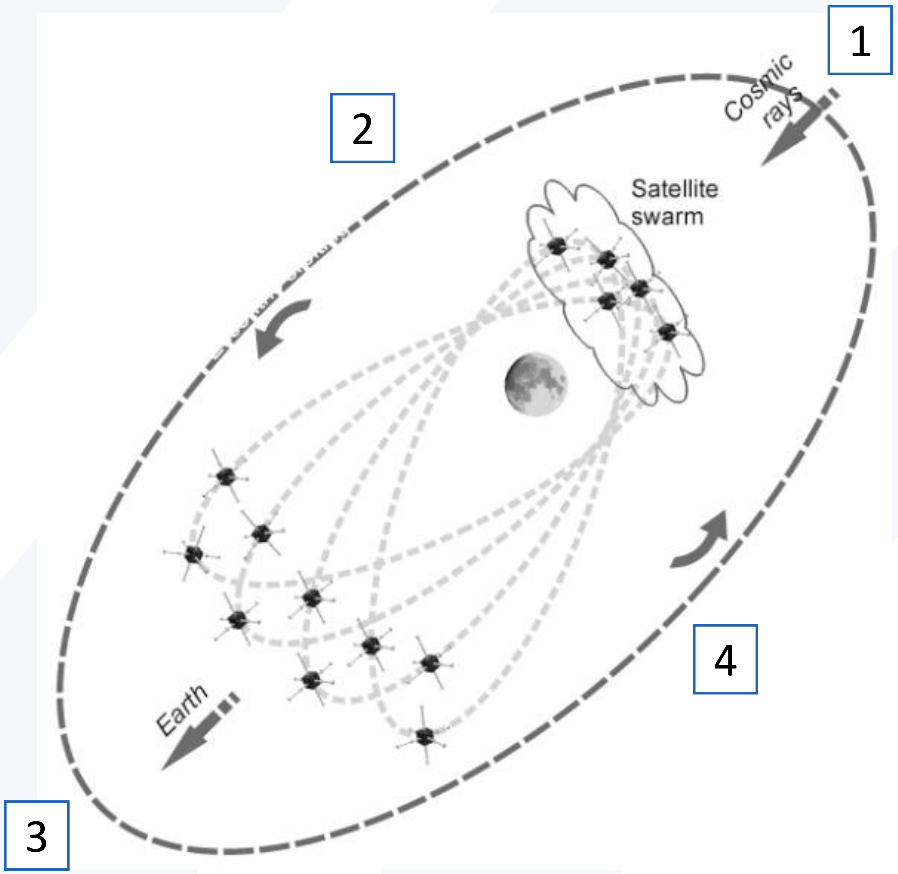
Objective of the mission

- Put a swarm of 100 nanosatellites in orbit around the Moon
  - No ionosphere!
  - Protection against RFI

Creation of a distributed radio-telescope in space

Operation

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



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

Graph theory-based approach

System description

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

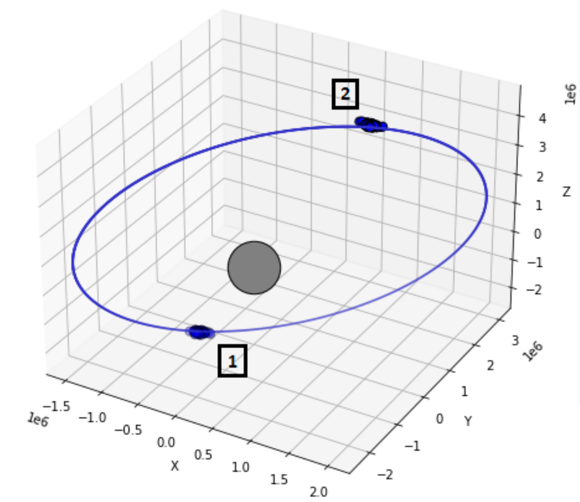
Dataset description

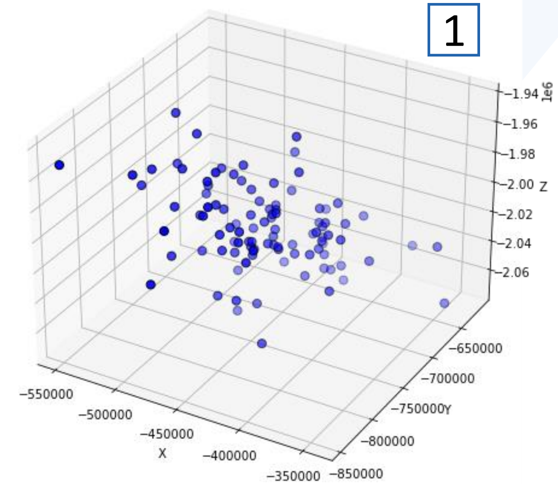
Data are synthetically generated in Matlab and follow Kepler’s laws.

- 100 nanosatellite tracks
  - Moon-centered (x,y,z) coordinate system
  - Positions sampled every 10 seconds
  - Sampling duration: 100,000 seconds (10,000 samples)
- Revolution period of the swarm: 5h (approx. 1800 samples)

Simulation tool

- Custom Python3 module: swarm_sim
- Definition of the Swarm and Node objects
- Basic operations
- Metrics computation
- Visualization…





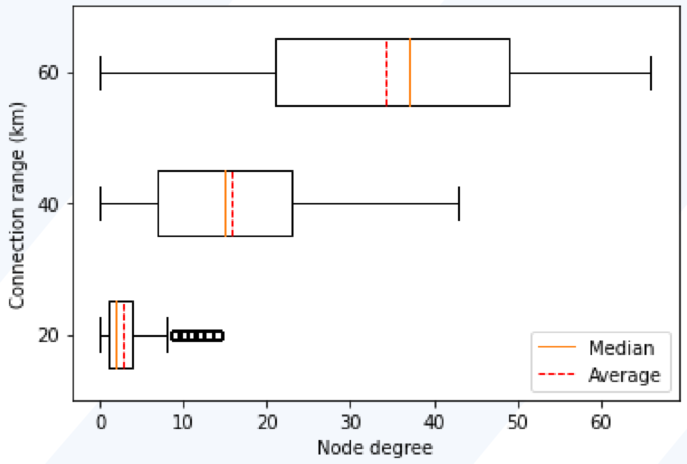
Connection hypotheses

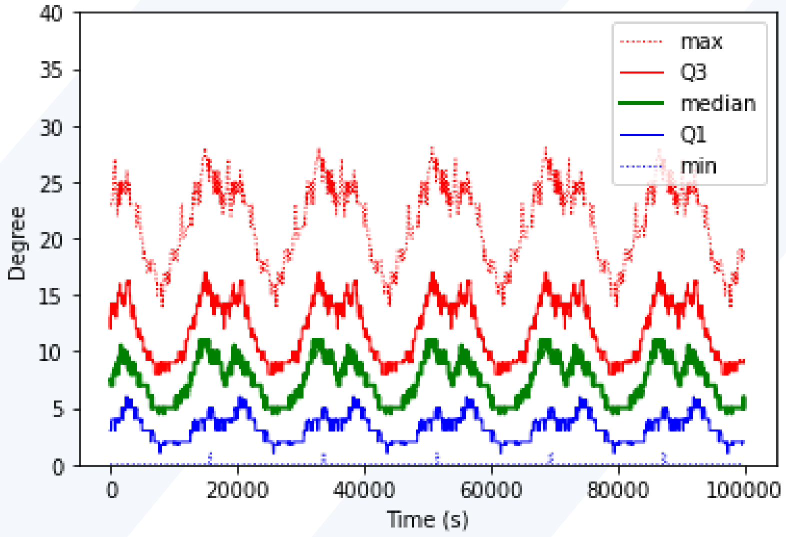
Two satellites can communiate iif there exists and ISL between them, i.e. they are in each-other's **connection range**.

- 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 (for now!)

Connectivity

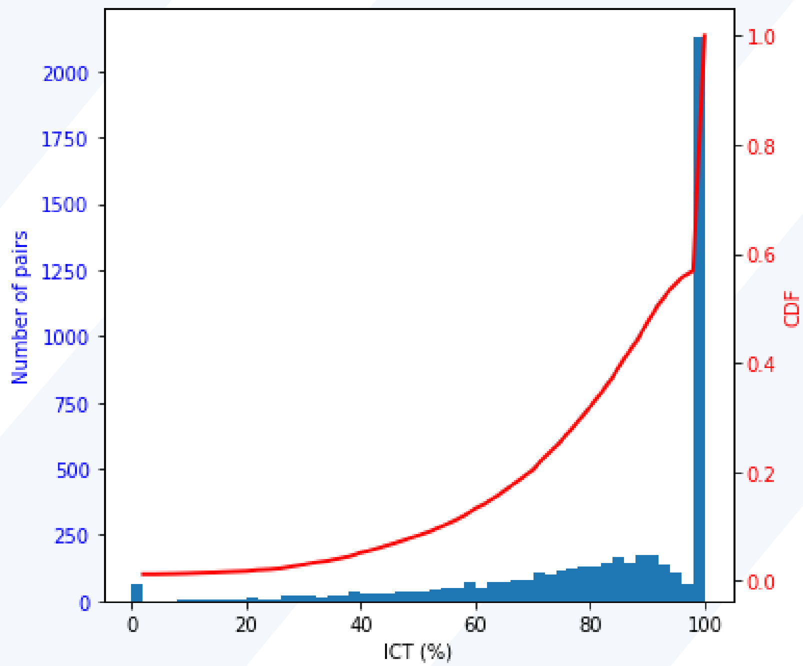
- Study of the neighborhood of the nodes
  - Direct (degree)
  - Extended (k-vicinity)
- Heterogeneous distribution of neighbors: presence of high- and low-density zones





Disponibility

- Inter-Contact Time (ICT) : measure of ISL disponibility
  - 0% ICT : permanent connection
  - 100% ICT : no direct contact between the nodes
  - Median >70% ICT



Conclusions on properties

- Heterogeneous connectivity and density: high- and low-density zones can appear, but the variation in node density is periodic.
- Heterogeneous disponibility: there exists a backbone of permanently connected pairs of node. The presence of such backbone implies that these nodes will consume more energy than the rest and thus go down faster.

A hybrid routing strategy is required.

Network overload control

Trade-off between architecture resilience and energy consumption

Problem definition

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

Proposed solution

Compute the image $\sqrt{N}$ times, by sharing less data packets

- Split the swarm into $\sqrt{N}$ node groups and share the data between those groups
  - Approach 1: Clustering (aggregate nodes into groups according to a given similarity)
  - Approach 2 : Division (split the graph into smaller subgraphs that are similar to the original graph)

Splittiong strategies

Technique	Graph clustering	Graph division
Objective	Regroup similar nodes together	Divide the graph into similar subgraphs
Measure of similarity	Average degree, clustering coefficient, graph density, group size, diameter…	
Pros	Nodes of a same group are homogeneous	Groups are fair with each other
Cons	Groups are not fair with each other	Groups can be poorly connected

Reminder of the metrics

- **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
- **Diamètre (Dia)** : longest shortest path between all pairs of nodes in the (sub)graph

To conclude…

- Nanosatellite swarms: highly heterogeneous distributed systems
- Optimisation of data transfert through a hybrid routing strategy
    - MANET/VANET
    - DTN…
- Trade-off between resilience and energy consumption and network congestion
    - Split the network into distinct groups to split the network load