RESILIENT NETWORK ARCHITECTURE IN A NANO-SATELLITE SWARM

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1. Presentation of the Work

1.1. Context: the NOIRE Study

NOIRE (*Nanosatellites pour un Observatoire Interférométrique Radio dans l'Espace*): a study to prove the interest of distributed radio interferometers in outer space

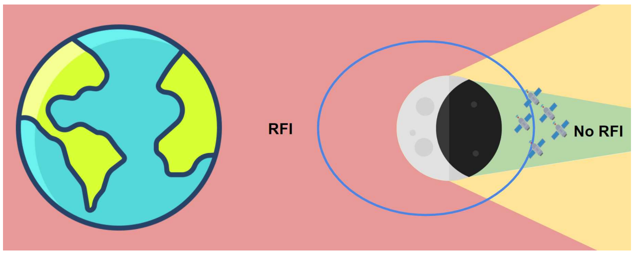


Figure 1: The Moon, a natural interference shield

Our system: a swarm of 100 nano-satellites in orbit around the Moon observing very low frequencies while being protected from the Earth's radio-frequency interferences (RFI)

1.2. Problem Definition: Intra-swarm Communication

Disseminate large amounts of observation data within the swarm:

- Potential link congestion and packet loss due to simultaneous transmissions
- Larger number of transmissions = higher energy consumption = faster power depletion
- Presence of critical nodes due to the heterogeneous satellite topology and network density.

1.3. Proposed Solution: Divide and Rule

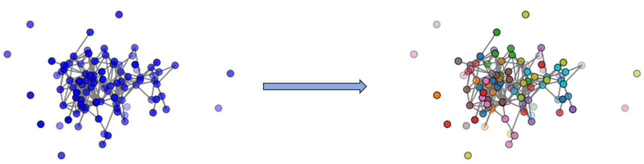
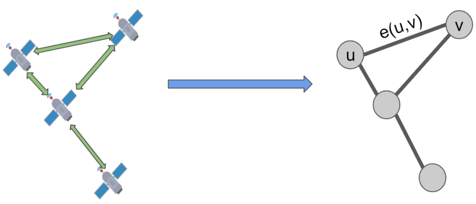


Figure 2: Fair network division process

2. Modelization

2.1. From Nano-satellite Swarms to Graphs



Swarm network		Graph $G(N,E)$
Nano-satellite	becomes	Node u
Inter-satellite link		Edge $e(u,v)$

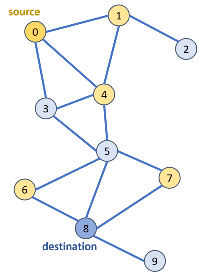
3. Analysis of the Resilience

Resilience: the capacity of a system to recover from faults.

3.1. Evaluation Criteria

Objective: evaluate the impact of network division on the resilience of the system

- **Redundancy**: how many efficient paths between node 0 and node 8?
- **Disparity**: how different are these paths from the shortest path?
- **Modularity**: how easily can one isolate the blue nodes if they are faulty?
- **Criticity**: what happens if node 5 fails?



3.2. Results on Resilience

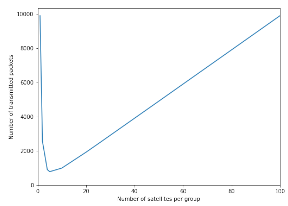
Resilience	Redundancy	Disparity	Modularity	Criticity (5%)
Before division	7.7 paths	56.4%	25.0%	16 nodes
After division	4.3 paths	70.4%	15.8%	4 nodes

Table 1: Impact of network division on the resilience of the system

4. Trade-off with the Robustness

Robustness: the capacity of a system to maintain functionality.

4.1. Energy Consumption: Divide to save Power



Fair network division can divide by 10 the energy consumption related to data transmission.

Consider the set of groups $C_G = \{c_0, c_1, ..., c_k\}$ obtained after fair division of graph G.

Number of transmitted packets: sum of intra-group and inter-group transmissions:

$$X(G) = \sum_{n \in N} |c(n)| - 1 \quad + \quad |C_G| \sum_{c \in C_G} (|C_G| - 1)$$

4.2. Network Efficiency: a Best Effort Strategy

Measure of the shortest paths lengths on the graph: the shorter, the better!

$$\Theta(G) = \sum_{u,v \in N} \frac{1}{l_{uv}} \times \frac{2}{|N|(|N|-1)}$$

4.3. Results on Robustness

Robustness	Packet transmission	Network efficiency
Before division	9900 packets	22.7%
After division	990 packets	36.0%

Table 2: Impact of network division on the robustness of the system