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On the Network Characterization of Nano-Satellite Swarms

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Abstract—Low-frequency radio interferometry is crucial to understanding the universe and its very early days. Unfortunately, most of the current instruments are ground-based and thus impacted by the interferences massively produced by the Earth. To alleviate this issue, scientific missions aim at using Moon-orbiting nano-satellite swarms as distributed radio-telescopes in outer space, keeping them out of Earth interference range. However, swarms of nano-satellites are systems with complex dynamics and need to be appropriately characterized to achieve their scientific mission. This paper presents a methodology based on graph theory for characterizing the swarm network system by computing graph theory metrics around three properties: the node density, network connectivity and ISL availability. We show that these properties are well-suited for highlighting a possible heterogeneity in a network and adapt a routing strategy accordingly. This work is the first milestone in defining the best-suited routing strategy within the swarm from the derived network properties.

Index Terms—Swarm of Nano-Satellites, Network Characterization, Graph Theory

I. INTRODUCTION

The study of the low-frequency range (below 100 MHz) is essential for many scientific fields, such as astrophysics for sky mapping and monitoring or the observation of the Dark Ages signals, which are signatures of the very early universe [1], [2]. Until now, the majority of low-frequency radio interferometry instruments are ground-based and provide high-quality observations of space. However, the capabilities of these instruments are limited by ionospheric distortions, terrestrial Radio Frequency Interferences (RFI), as well as a complete reflection of radio waves below 10-30 MHz [3]. Therefore, the cosmic radio signals that are weak in terms of power can be easily altered if not completely masked.

One solution to this problem is to create an interferometer directly in space: the Nano-satellites for a Radio Interferometer Observatory in Space (NOIRE) [4] study investigates and proves the feasibility of using a swarm of nano-satellites for low frequency radio observation in space. Indeed, a swarm of approximately 100 nano-satellites orbiting the Moon is

highly protected from the Earth's RFI, and thus appears as a promising solution to the interference problem met by ground-based telescopes.

The setup and configuration of a swarm of nano-satellites as a space observatory is a challenging problem in terms of communication, as the network relies solely on wireless Inter-Satellite Links (ISL). It is possible to approximate this system as a Wireless Sensor Network (WSN), with the particularity that the average inter-satellite distance goes up to 50 km (interferometry instrument requirement), making it a very low-density network. Besides, the satellites move at an average speed of 1 to 10 km/s, making the swarm a highly mobile system and adding constraints to the communication model.

But most importantly, the system needs to operate in a distributed manner. Indeed, unlike traditional observation satellites that usually carry one or many measuring devices, a swarm of nano-satellites consists of a single instrument distributed over many satellites. Thus, each satellite collects observation data from space, then shares them among the swarm to compute one single image of cosmic rays. This image is a matrix of cross-correlations between all data collected by every satellite and shared among the swarm.

The main challenge is thus to disseminate significant amounts of data within the swarm, which raises major communication issues. First, the simultaneous propagation of several gigabytes of data over a radio channel by each satellite can lead to potential link congestion, delay, and packet loss. Then, the energy consumption of the swarm is proportional to the amount of data shared between the satellites. Therefore, a trade-off has to be made to limit the total energy consumption of the swarm to alleviate these issues and prevent too early energy depletion of the satellites. It becomes primordial to correctly measure the system: finding an optimal routing strategy to perform this data collection cannot be conceived without proper network characterization.

In this context, we focus on studying the specificities of a swarm of nano-satellites on the telecommunications level and,

more precisely, on the characterization of the network layer to further determine a suitable routing scheme. We present a set of metrics based on graph theory that prove to perfectly grasp the network dynamics and heterogeneous nature when appropriate. The choice of routing strategy is only discussed and oriented at this stage, but will be thoroughly studied in a future work. We first present, in Section II, the state-of-the-art related to routing challenges. Section III describes the nano-satellite swarm model, then the network properties are derived in section IV. Finally, section V summarizes the essential results and perspectives of our work.

II. RELATED WORK

Similar case studies exist in the literature, such as the Orbiting Low-Frequency Array for Radioastronomy (OLFAR) project [5]. Their objective is to use a swarm of at least 50 nano-satellites as a distributed radio-telescope orbiting the Moon. In this paper, the authors focus on the relevance of dynamic node clustering to minimize the energy consumption related to data sharing. The authors demonstrate that classic clustering algorithms (such as global k-means or MOBIC) are not well-suited for highly mobile Wireless Sensor Networks (WSN). Thus, they provide a slave-master algorithm that proves to be a better solution for this topology. Regarding the same OLFAR project, in [6], the authors emphasize the critical nature of the downlink communication from the swarm to the Earth and present a resilient transmission mechanism.

To this day, routing algorithms are better studied on satellite constellations or mobile WSN. In [7], the authors propose an IoT-compliant routing algorithm, named Multi-Level FREAK, which improves routing performances in a network where nodes can disconnect from their destination. Their solution requires very few memory and computation power, but their case study is different from ours: indeed, our objective is to share data with a large subset of nodes, whereas their objective is to send data to a precise destination. In [8], the authors introduce a simple yet efficient network characterization methodology for choosing an adapted routing scheme. They show that in the case of satellite constellations, which are quasi-deterministic mobile networks, an opportunistic routing scheme is better suited as the studied network architecture is closer to a Delay-Tolerant Network (DTN) than a Mobile Ad-Hoc Network (MANET).

However, in the case of a swarm of nano-satellites, abrupt changes in topology can occur. One solution to this problem is proposed in [9], where the authors introduce the HYMAD algorithm. HYMAD is a hybrid DTN-MANET routing scheme that relies on topology information to adapt to the node density of the network, i.e., the algorithm behaves as a MANET routing scheme within highly dense zones, and a DTN scheme between these zones where the density is lower. The authors prove the efficiency of their algorithm in terms of delay and delivery ratio. Another solution is to rely on a routing scheme based on swarm intelligence: in [10], the authors introduce an intelligent algorithm inspired by ants colonies, AntHocNet. Their algorithm is adapted for MANET and proves to be more

efficient regarding delay jitter and routing overhead than a classic algorithm such as AODV.

Finally, a promising approach for determining a routing scheme for a swarm of nano-satellites is to study Flying Ad-Hoc Networks (FANET), and more specifically, swarms of drones. Indeed, the characteristics of FANET are very close to our study case: the node mobility is very high, the average density is low, and there are fast topology changes. The mobility model is also pre-determined in most cases. In [11], the authors prove that it is possible to exploit the spatial multiplexing of the wireless channel by decreasing the connection range and implementing multi-hop routing. They evaluate the performances of MANET routing protocols such as OLSR and AODV, and Greedy Perimeter Stateless Routing (GPSR) [12] in a swarm of drones. A survey on FANET communication protocols for physical, MAC, network, and transport layers is also proposed in [13].

III. MODEL DESCRIPTION

We present in this section the objectives and requirements of our study, then describe the modelling of the swarm network as well as the basic connection hypotheses.

A. Objectives and Requirements

The adaptability of swarms of nano-satellites is a strong advantage: such missions can offer a wide spectrum of study opportunities. In addition, a lunar orbit is particularly well-suited for these missions, as the swarm is not disturbed by interferences coming from the Earth.

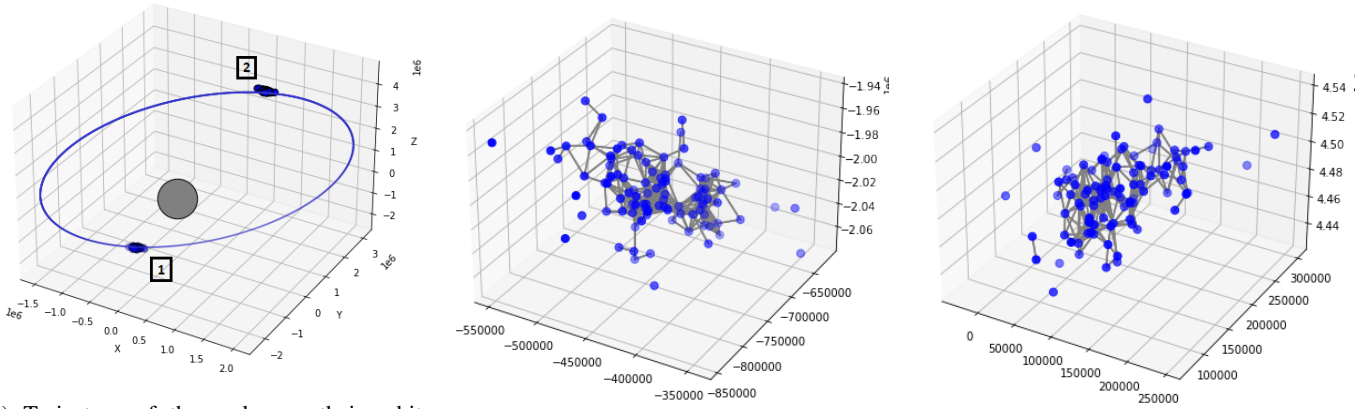
At each revolution around the Moon, scientific missions, like those described in the NOIRE study, operate in at least four steps:

- 1) Observation: each nano-satellite collects raw data from space.
- 2) Inter-satellite transmission: each nano-satellite broadcasts their data to the others and gathers the data from the other nano-satellites. This step is the focus of the paper.
- 3) Computation: each nano-satellite computes a part of the overall space image combining the data collected and received from the others.
- 4) Swarm-to-Earth transmission: the swarm downlinks the computed space image to a base station on Earth. This step is thoroughly studied in [6].

The objective of our study is network-based. The main goal is to determine a methodology for characterizing the properties of a swarm topology and thus derive the most suited routing scheme for data propagation within the swarm. Indeed, understanding the network dynamics is essential to efficiently share the data within the swarm while optimizing the energy consumption and the duration of the most interesting phase for the scientific community: the observation of space.

B. Description of the Network

Let us model the swarm network at each timestamp $t \in T$ as a graph $G_t(N_t, E_t)$ with a set of nodes N_t , representing the



(a) Trajectory of the nodes on their orbit around the Moon.

(b) Topology of G at snapshot (1).

(c) Topology of G at snapshot (2).

Fig. 1: Dynamic topology of graph G . The orbit of G is defined as the average orbit of its $|N|$ nodes. Each node position is derived with a random offset to the first node position, which is fixed (see Section IV-A).

nano-satellites, and a set of edges E_t , representing the ISL. We assume the nodes operate in a faultless manner, *i.e.*:

$$\forall(i, j) \in T^2, |N_i| = |N_j| = |N|$$

This condition guarantees that the number of nodes in the graph remains constant with time. In our case, the studied network is a swarm composed of $|N| = 100$ nano-satellites orbiting the Moon, as depicted in Fig. 1a. The nano-satellites are all identical and use omnidirectional antennas to communicate with each other. The swarm system has the following properties:

1) *Mobility*: the nano-satellites are mobile within the swarm according to a quasi-deterministic mobility model, *i.e.*, $\exists(i, j) \in T^2 \mid E_i \neq E_j$. This property highlights the dynamic nature of the ISL within the swarm network as depicted in Fig. 1b and Fig. 1c. The mobility model is more thoroughly studied in section IV.

2) *Temporal Drift*: the swarm mobility with respect to the Moon is pseudo-periodic, *i.e.*, a small drift over time is randomly induced for each nano-satellite.

These properties imply a temporal evolution of the swarm topology. Intuitively, the routing strategy should be able to adapt to topology changes.

C. Connection Hypotheses

The connectivity within the swarm is exclusively based on ISL. Let $e_t(u, v)$ be the edge between two nodes u and v of the graph G at the time t , and $d(u, v)$ the Euclidean distance between these nodes. The set of edges E_t is defined as follows:

$$E_t = \{e_t(u, v) \mid d(u, v) \leq R_G\} \forall (u, v) \in N_t^2 \quad (1)$$

where R_G is the connection range of the model: it is independent of time and identical for all nodes at all times. We also assume that each ISL is a duplex link, *i.e.*, $e_t(u, v) = e_t(v, u)$. Additional connection hypotheses are listed below:

- All data messages are identical in size;

- every message is broadcasted. This hypothesis is based on the presence of the omnidirectional antenna on each nano-satellite;
- each node of the network can forward messages in the manner of a router;
- the throughput can be adaptive.

A trade-off has to be made on the throughput, as a high throughput reduces the transmission duration and thus gives more time for the observation phase. Still, it also increases the energy consumption of the nano-satellite.

IV. CHARACTERIZATION OF NETWORK PROPERTIES

In this section, we first describe our working dataset and present the metrics used for characterization. Then, we present our experimental evaluation and discuss the results.

A. Description of the Dataset

To determine the properties and features of a swarm of nano-satellites, we use synthetic data generated in Matlab. Each nano-satellite orbits the Moon and follows Kepler's laws. The trajectory parameters of the first node are set manually on a given orbit. In contrast, the parameters of the others are generated dynamically with a random offset to the first one. The dataset has the following specificities:

- The data represent the coordinates of $|N| = 100$ nodes in the Moon-centered coordinate system, distributed in a sphere of 100 km in diameter in its initial state;
- the (x, y, z) coordinates of the nodes are sampled every 10 seconds;
- the simulation duration is $T = 100,000$ seconds;
- a nano-satellite performs a complete revolution in approximately 18,000 seconds.

Classic geolocalization is impossible to achieve because of the lack of GPS tracking in outer space. The Moon-centered

coordinate system is convenient in this case, as the nano-satellites will process the coordinates to perform a distance-based peer localization. Relative distances and positions are indeed known because they are necessary for interferometry image computation.

B. Metrics of Interest

In this paper, we adopt a graph theory approach because graph theory metrics are well-suited for network characterization [14]. We focus on characterizing three significant network properties: the node density, the network connectivity, and the ISL availability.

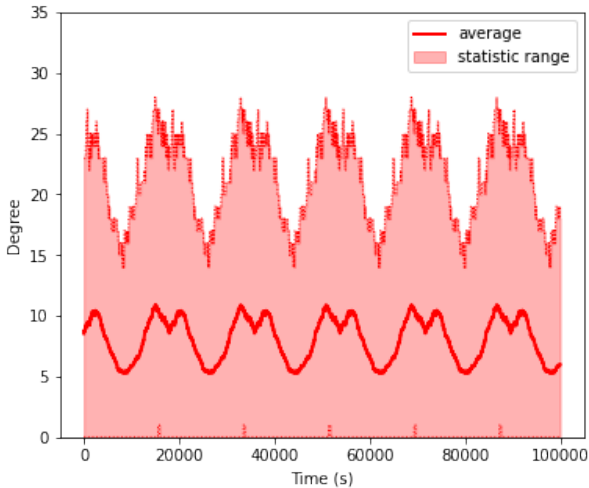


Fig. 2: Evolution of the degree distribution with time through its average value and statistical range.

1) *Node Density*: the node density is generally characterized by the node degree, denoted for a node u as $\delta(u)$, which is the number of nodes within its connection range. By definition, the degree strongly depends on the chosen connection range. The knowledge of the neighborhood can be extended beyond the connection range by computing the k -vicinity [18]. The k -vicinity, denoted $\delta^k(u)$, characterizes this extended neighborhood as the number of nodes reachable within at most k hops from the source node (note that $\delta^1(u) = \delta(u)$). The analysis of the k -vicinity is of interest in our case because it shows that some nodes with few direct neighbors can reach a larger set by performing additional hops, making it a valuable metric for routing configuration. It can be useful in two cases:

Case 1: there is a limited number of message copies to transmit, and a choice has to be made for the next hop: a node with a larger k -vicinity would be preferred over an isolated node. This case is not relevant here because the messages are broadcasted and thus not limited in terms of copies.

Case 2: we need to optimize the energy consumption by minimizing the number of hops of a message: transmitting the message in priority to nodes with a high k -vicinity can decrease the total duration of the transmission. By doing so, it is possible to adapt the route of the messages and optimize

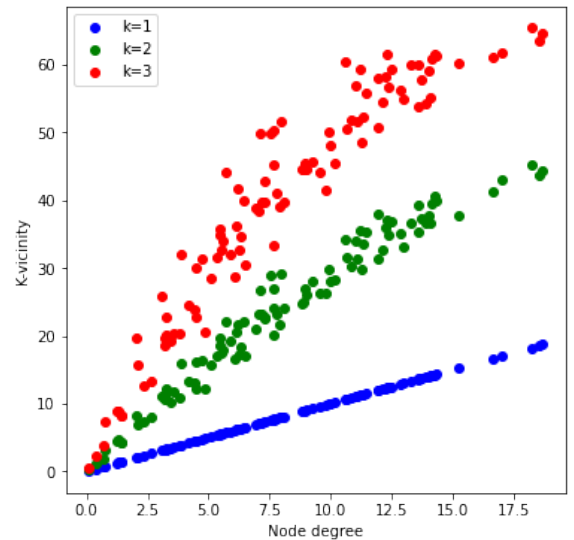


Fig. 3: Average k -vicinity with respect to node degree, for three different values of k .

the propagation. This is the case to be studied in the context of our mission.

2) *Network Connectivity*: the network connectivity can be characterized through various metrics, but we choose to focus only on the graph density and the connected components. The graph density (not to be confused with node density) gives an overview of the connectivity by evaluating the proportion of ISL in the graph, and is defined as follows:

$$\rho_t = \frac{2|E_t|}{|N|(|N| - 1)}$$

The second part is the analysis of the connected components, which are defined as groups of nodes connected together. The higher the number of connected components, the weaker is the connectivity of the graph. We denote \mathcal{C}_t the set of connected components at a time t :

$$\mathcal{C}_t = \{c_t^i | c_t^i \subset N_t\}$$

and

$$c_t^0 \cup c_t^1 \dots \cup c_t^n = N_t$$

3) *ISL availability*: we characterize the availability of the ISL in the swarm by analyzing the Inter-Contact Times (ICT) [17]. The ICT is defined, for a pair of nodes u and v , as the proportion of time spent without a direct connection between them, and is denoted $\tau(u, v)$. As such, the analysis of the ICT distribution provides direct information on the availability and consistency of the ISL within the swarm. The ICT is usually computed on a given period of time (*e.g.* on a complete revolution around the Moon).

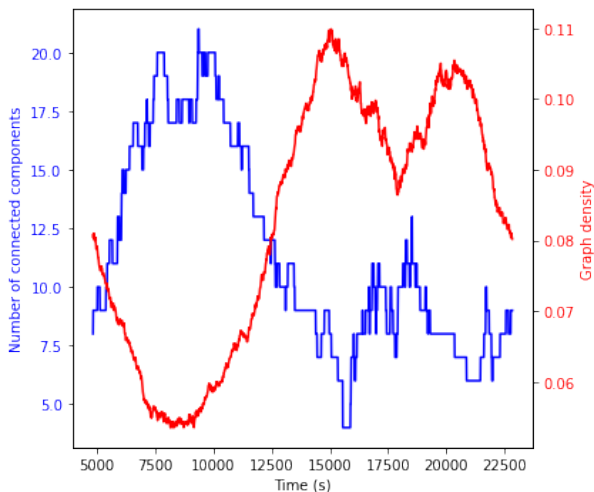


Fig. 4: Cross-evolution of the number of connected components and the graph density over a complete revolution around the Moon.

C. Experimental Evaluation and Results

We model the swarm system in Python3 by creating a simple yet adapted simulation tool called *swarm_sim*¹. This simulator is a Python3 module that comprises Node and Swarm objects as well as many basic operation functions (such as trajectory simulation, metrics computation, etc.). We choose to implement our swarm simulator because the existing frameworks do not match our case study. No tool is efficient in both networking and spatial mechanics: indeed, in [7], [9], the authors use the DTN simulator The ONE presented in [15], which performs well in network-layer simulation from 2D data, but cannot simulate 3D data in the Moon-centered coordinate system. The Hypatia simulator is presented in [16] and displays many functionalities for constellation networks. However, in this model the ISL are static and not dynamic, making this simulator not adapted to swarms of nano-satellites.

Notation	Definition	Value
R_G	Connection range	30 km
$ N $	Number of nodes	100
T_S	Simulation duration	18,000 s
k	k-vicinity depth	[1; 2; 3]

TABLE I: Simulation parameters.

The global parameters of the simulation are listed in Tab. I. At each timestamp, we analyze the network connectivity by computing the number of connected components and the graph density. The evolution of these metrics is drawn in Fig. 4. We also compute the ICT for all pairs of nodes in N_t : the ICT distribution is drawn in Fig. 5. In parallel, for each node, we compute the degree and k-vicinity to grasp the dynamics of the node density. Fig. 2 shows the evolution of the distribution of node degrees through its average value and statistical range.

¹Link to the source code available upon request.

Fig. 3 shows the evolution of the average k-vicinity with respect to the node degree.

1) *Results on the Node Density*: because the average node degree is strongly linked to the inter-satellite distances, the evolution of the instantaneous average node degree shown on Fig. 2 highlights a periodicity in the mobility within the swarm and thus in the node density. The minimum node degree is mostly equal to 0, even when the average degree is high: it shows that the statistical range of node degrees within the swarm can be very wide, with highly and weakly connected nodes. On the other hand, the evolution of the average k-vicinity with respect to the node degree as drawn in Fig. 3 was predictable: intuitively, we assumed that the extended number of reachable nodes would increase with additional hops, which is indeed the case in this graph. By performing only one additional hop ($k = 2$), it is possible to double the number of node neighbors, no matter the degree of the node.

2) *Results on the Network Connectivity*: Fig. 4 shows the evolution, on a complete revolution around the Moon, of the number of connected components in the graph as well as the graph density. The cross-evolution of these metrics is interesting because they are inverted: a high number of connected components implies fewer edges in the graph, hence a low graph density. On the contrary, a very high graph density implies that the nodes are connected within a single, bigger component. We can also notice the graph density follows the same evolution as the average node degree. Nonetheless, the highest graph density value merely equals 0.11, *i.e.*, we can observe up to 11% of ISL out of all possibilities in the strongest connected state.

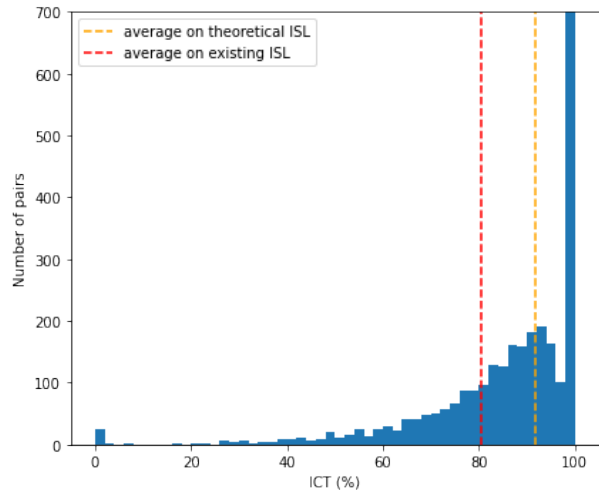


Fig. 5: ICT distribution for all pairs of nodes. Pairs on 100% ICT are considered theoretical only. The average value on existing ISL is over 80%.

3) *Results on the ISL availability*: Fig. 5 shows the ICT distribution computed for each theoretical ISL on a complete revolution around the Moon. We call theoretical ISL all the possible pairs of nodes, while existing ISL refers to the edges actually observed in E_t . In this figure, the average ICT on

existing pairs is above 80%, and the average on theoretical ISL is higher. This means that an ISL is available less than 20% of the time on average. But the most interesting information are the extreme values. First, the large number of unavailable links, represented by the pairs at 100% ICT, shows that some pairs of nodes are too far away from each other and will never establish a direct contact (these pairs are not considered existing ISL). We can also notice that a significant number of pairs are at 0% ICT, which means they are always connected and thus act as a backbone in the network.

Although the analysis of these five metrics provides various information on the swarm network, the central characteristic is its important heterogeneity on all studied aspects.

D. Routing Perspectives

The characterization of the nano-satellite swarm highlights the peculiar nature of the network. Indeed, the overall connectivity of the network is weak (based on the average number of neighbors and the ISL availability) and evolves periodically in orbit around the Moon. These results encourage us to prefer a DTN routing scheme over a MANET one. However, an analysis based on average values and tendencies alone can hide the specific dynamics of the network. In our case, the network is actually very heterogeneous in terms of density, connectivity, and even ISL availability. Therefore, the routing scheme will perform better in some cases than in others. Thus, the best solution is to develop a hybrid approach to alleviate the heterogeneous nature of the network, *e.g.* with a MANET routing within the high-density zones and DTN routing within the low-density zones, as proposed in [9] with the HYMAD protocol.

V. CONCLUSION

This paper has highlighted the importance of studying nano-satellite swarm systems more thoroughly for the scientific community. We have presented an efficient, methodology based on graph theory for the characterization of any swarm network operating in space, intending to grasp the dynamics of the network and derive its properties to determine the most adapted routing scheme. Indeed, a wireless mobile network may require either MANET or DTN routing schemes, but a complex system such as a swarm of nano-satellites orbiting the Moon needs a hybrid protocol to adapt to any situation in space.

In our case, we showed that the node density, network connectivity and ISL availability within the swarm oscillate periodically according to the position of the swarm around the Moon and are very heterogeneous. Hence, the routing strategy must be adaptive to be efficient at all times and for all nodes. Because we have high- and low-density zones within the swarm, a hybrid MANET/DTN protocol such as HYMAD seems to be the best-suited routing scheme based on our simulation results.

In our future work, we aim to study the energy consumption related to the data transmission within the swarm, and find the best way to minimize it. Our first objective will be to limit

the number of transmissions of data packets from one node to the rest of the swarm by performing a fair graph division. Then, we will study the impact of different routing strategies on the energy consumption of the swarm, which will be a key criterion for the choice of the routing strategy.

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