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Latency optimization in Centralized and Decentralized Coordination of Time-Varying Evolutionary Satellite Networks: The Impact of packet size

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Abstract

Effective minimization of latency in satellite network infrastructures is critical for ensuring efficient data transmission, communication, and resource allocation in space operations. With the growing number of satellites and increasing complexity of in-space activities, conventional centralized optimization methodologies face scaling limitations, requiring the exploration of decentralized coordination techniques.

This paper presents a study on the effect of packet size on latency in decentralized coordination of evolutionary satellite network infrastructure. Building upon previous research, our investigation focuses on formulating a time-varying dynamic graph framework tailored for decentralized optimization of satellite networks. This includes the performance characterization of dynamic space networks and the comparative analysis of the time to spread the data with different federation topologies.

Decentralized optimization distributes decision-making processes across multiple network nodes, enabling each node to make informed decisions based on local data, constraints, and partial knowledge of other nodes. Through exploring specific operational assumptions on network topology and communication, we present scenarios where decentralized approaches outperform traditional centralized satellite network management, offering enhanced reliability, reduced data latency, scalability, and robustness.

Our paper presents findings on the influence of packet size on latency in decentralized settings. We identify the advantages that delineate the operational advantages of decentralized coordination over centralized management in satellite networks. By illustrating our approach through applying it to an object detection use case, we define the use case of decentralized coordination for dynamically allocation of resources within federations of satellites. Our research aims to establish fundamental conditions and operational criteria for designing future decentralized satellite networks, facilitating the dissemination of information among satellites in orbit and promoting sustainable utilization of limited in-space resources and autonomous space operations.

Keywords: Satellite Coordination, Federated Satellite Systems, Satellite Network Infrastructure, Spacecraft operations, Constellations, Resources allocations

1. Introduction

In everyday life we utilize services delivered by terrestrial infrastructure that has helped the progress of technology over the last decades such as transportation, energy, internet, healthcare, and so on. Missions in orbit such as the Global Positioning System (GPS) and Galileo Europe's Global Satellite Navigation System (GNSS) [1] are examples of infrastructure that humanity built in orbit to deliver services on Earth. In addition to positioning, navigation, and timing (PNT) companies of the likes of SpaceX, One Web, Spire, and Kuiper [2]are launching satellites for enabling connectivity and for observing and monitoring our planet. As a consequence of such growth, concepts enabling support and maintenance of in-space infrastructure are becoming of relevance. In-orbit servicing is an opportunity for enhancing the operations of constellations and federations of satellites in space [3], [4]. As the population of orbiting satellites grows, services allowing for coordination and management of traffic in-orbit are also likely to be required. Satellite constellations require coordination amongst spacecraft, especially considering the behavior of space networks, where the dynamic and topology of participating nodes are time-varying and evolutionary in nature.
Researchers have conducted and analyzed initial studies on the optimization of time-varying evolutionary networks for evolutionary space infrastructure, focusing on the benefits of decentralized coordination in space network infrastructure[5]. In this paper we expand previous research on optimization of time-varying

evolutionary satellite networks to analyze the effect of packet size on latency in both centralized and decentralized coordination of evolutionary satellite network infrastructure or federations of satellites.

This paper introduces the approach used for analysis and simulation of space networks. It includes a satellite network propagation module, with the definition of the topology of the network, and a communication and data handling module for distributing the different data in the space network. We exemplify the approach on an object detection use case in which the satellites coordinate with each other for detecting, observing, and tracking objects in space, such as debris or other satellites, while sharing information about the position or images of detected objects.

We discuss the comparison of performance of different network topologies as a function of varying network centrality.

The remainder of this paper is structured as follows. Section 2 introduces related work for analyzing the context in which the research is conducted. Section 3 provides a problem formulation and research methodology. Section 4 discusses the simulation model that has been developed to implement the analytic approach of time-varying evolutionary satellite networks. Finally, Section 5 illustrates a discussion of the results of an object detection use case, highlighting the potential impact of decentralized networks in space, and outlining avenues for future work.

2. Related works

The coordination of satellite networks is a significant area of research particularly as satellite constellations grow in size and complexity. This section reviews key studies related to centralized and decentralized coordination methods, network communication models, and the impact of packet size on latency.

Satellite coordination, including planning and scheduling is typically resolved in a centralized fashion, where a single central coordinator specifies the actions of every satellite [6], [7], [8]. Centralized coordination simplifies the decision-making process, it is easier for implementing global mission objectives, and potentially involves a lower degree of complexity for on-board software. However, centralization has the disadvantage of exposing a single point of failure for the mission, higher communication bandwidth needed with ground station, and lower scalability for large satellite federations. Hence, decentralize coordination addresses both the system's robustness and the vulnerability of a single point of failure [9], [10]. Researchers implemented different approaches to study the best coordination techniques for planning and scheduling of operations in decentralized way, such as the Distributed Constraint Optimization Problems (DCOP) algorithms developed by Zilberstein [11], or Distributed Observation Allocation for a Large-Scale Constellation approach presented by Parjan and Chien [12]. Existing approaches rely on large volumes of messages that every agent has to communicate for an effective coordination, effectively creating overhead impacting network capacity. The effect of growing packet size is interesting to evaluate to establish bounds of applicability of the proposed coordination techniques for different space networks infrastructure. Despite the extensive research on satellite coordination and latency, there are still gaps, particularly concerning the scalability of decentralized coordination for large satellite federations and the impact of varying packet sizes on latency. While decentralized networks have shown to reduce latency research on their performance in mega-constellations is still evolving.

Although several works focus on optimizing communication protocols for satellite networks, few explore the dynamic interaction between network centrality and packet size on propagation latency. This paper aims to fill this gap by examining the performance between centralized and decentralized coordination, focusing specifically on the impact of packet size on latency in time-varying, evolutionary satellite networks.

In order to investigate these interactions, the following section outlines the problem formulation, detailing the performance evaluation criteria for the coordination of time-varying evolutionary satellite networks, with a focus on how various factors, such as the number of satellites, packet sizes, and network architectures, affect data dissemination latency.

3. Problem formulation

This section presents the problem formulation for outlining the performance of the coordination of time-varying evolutionary satellite networks, in terms of time to spread the data-information among all the nodes of the network. We considered the effect of different number of satellites N_s, different packet sizes and different network coordination architectures.

3.1 Mathematical Formulation

The problem of reducing latency in the transmission of data within a satellite network can be modeled as a network optimization problem. We aim to minimize the total time required for data dissemination across a network of N satellites.

The key factors include:

- N_s : Number of satellites in the network.
- D: Packet size to be propagated through the network.
- T_{ij}: Time taken for the satellite i to be able to transmit data to satellite j
- d_{ij}: Distance between satellite i and satellite j.
- R_{ij} : Data rate between satellite i and satellite j.

- C: Network centrality (degree of centralized control).

3.1.1 Objective Function

The objective is to minimize the total latency T for the data to propagate through the entire network. The total latency is expressed as the sum of the transmission times across all pairs of satellites *i* and *j*:

$$T_{total} = \sum_{i=1}^{N_s} \sum_{j=1, j\neq i}^{N_s} T_{ij} \left(D, R_{ij}, d_{ij}, C, info, t\right) \quad (1)$$

where T_{ij} depends on both the packet size *D*, data rate R_{ij}, on the topology of the varying network that affects the distance among the satellites d_{ij}, the degree of centrality of each node C, on the satellite that possess the information to be spread *info*, and the time step *t*.

Satellites are not stationary and move along predefined orbits, so the positions of satellites change over time, affecting both the distance d_{ij} and the connectivity:

$$\boldsymbol{x_i}(t) = f(\boldsymbol{x_i}(0), t) \quad (2)$$

where $\boldsymbol{x_i}(t)$ represents the position of satellite *i* at time *t*, and $f(\cdot)$ represents the orbital propagation function.

3.1.2 Design Variables

A sensitivity analysis of the problem considers changing the values of the following design variables in specific ranges to check the variations in the propagation time of the data among the nodes of the network. The most relevant design variables are listed in Table 1.

Table 1. Design variables

Design Variable	Description	Range	Unit
N_s	Number of satellites	[20÷10000]	-
$n_{centsats}$	Number of centralized nodes	[10, 20, 50, 100 N_s]	-
D	Packet size	[1, 1680, 10k, 20k, 30k, 40k, 50k, 60k, 70k, 80k, 90k, 100k]	bits

The number of satellites is the primary design variable allowing to study data propagation in varying satellite architecture scenarios, from small federations of satellite to mega constellations. We consider the effect of the degree of centrality, changing the number of centralized nodes. To clarify the different coordination considered, we first present the *complete centralized coordination,* where only one single centralized communicates with all the satellites, but the other nodes cannot communicate with each other, as shown in Fig.1. Hence, the central node has a degree of centrality equal to the number of satellites and the other satellites have a degree of centrality equal to 1.

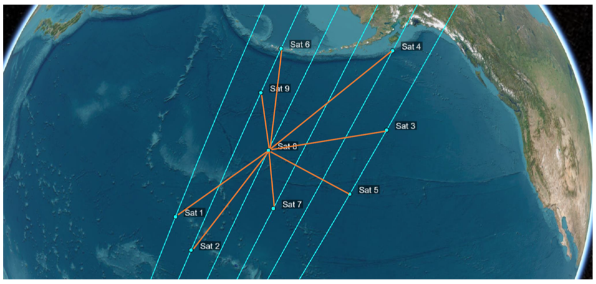

Figure 1. Complete centralized coordination

Then, we increase the number of centralized nodes, increasing the degree of centrality for all the nodes of the federation, with the capability of communicating with more satellites.

The ultimate case considers the *complete decentralized coordination*, where all the nodes can communicate with each other, and there is no need for a centralized node, as shown in Fig. 2. Hence, all the nodes have the same degree of centrality, equal to the number of nodes minus one.

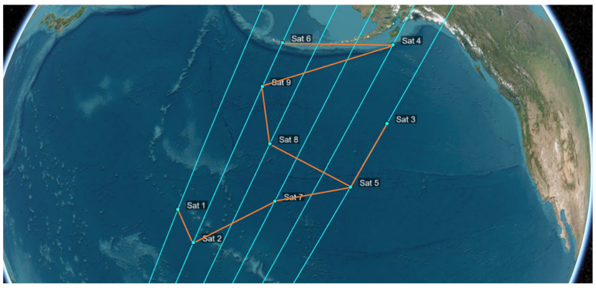

Figure 2. Complete decentralized architecture

Building on this discussion of centralized and decentralized coordination, the next section describes the simulation model employed to evaluate how these varying coordination schemes, along with network size, influence data propagation in satellite networks.

4. Simulation Model

We study the data propagation through an algorithm for simulating data propagation in satellite networks. We simulate networks of varying sizes with satellite counts N_s ranging from small-scale constellations to large mega-constellations. We test these networks under both centralized and decentralized coordination schemes.

We vary the network centrality C to assess its impact on data propagation. Centralized networks have a central node managing data flow, while decentralized networks allow peer-to-peer communication.

The simulation model consists of an orbit propagation module, an imaging payload and a communication and data handling module. The different modules interact with each other to guarantee the effectiveness of the algorithm, consequently we present the simulation flow in Fig. 3.

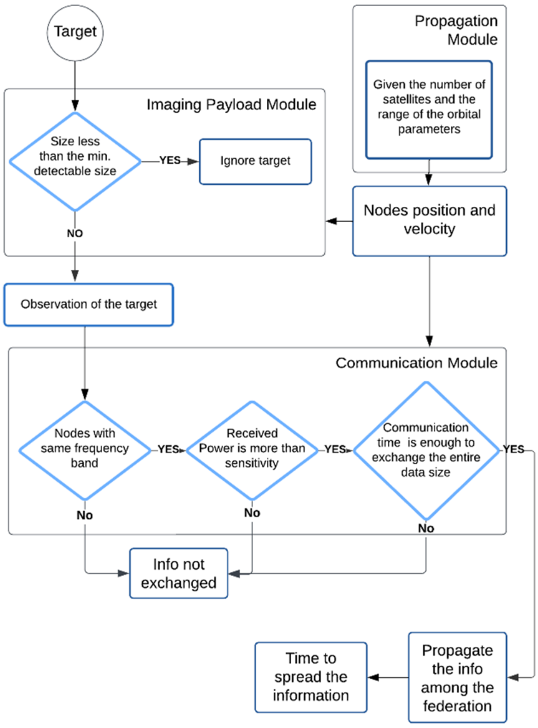

Figure 3. Simulation Flow

The simulation flow uses a scenario in which a federation of satellites coordinate for observing objects in space. In this scenario, a federation of satellites performs the task of observing and tracking objects in space, such as debris or other satellites. When one satellite in the federation detects or observes a target, it must share this information with the rest of the network. The satellites coordinate with one another to ensure that the data, such as the position, speed, or images of the detected object, is efficiently propagated throughout the entire network. This coordination allows for timely and accurate tracking of the target, enabling the satellite federation to act as a cohesive system for space object monitoring and avoidance.

First, a propagation module propagates the position of velocities of all the observers and the targets. If the target has a dimension that is larger than the detectable size from the observer, then the object can be observed. The data about the target then enters the communication module, where we check the capabilities of the different nodes to exchange the information. This process ensures that the nodes have the same frequency band, the signal power at the receiver exceeds the sensitivity of the receiving antenna, and the communication link remains long enough to exchange the full information. Once these conditions are met, the satellites propagate the data among each other, and when the entire federation has received the information, we calculate the time taken to spread the data.

The following sections describe the different modules in detail.

4.1 Orbit Propagation Module

The orbit propagation module initializes the orbit parameters for each node of the federation.

We define the different orbital elements: semi-major axis a, eccentricity e, inclination i, Right Ascension of Ascending Node Ω, argument of perigee ω and true anomaly ϑ, to propagate the orbits.

We consider different topologies of the federation, starting from a federation of satellites in Sun-Synchronous Orbit (SSO), with an altitude of 700km, null eccentricity, and a Right Ascension of Ascending Node Ω and a true anomaly of the various nodes to be equally distributed between 0 and 360 degrees, and we use the formula 3 to evaluate the inclination.

$$\dot{\Omega} = -9.96 \left(\frac{R_{Earth}}{a}\right)^{3.5} \cos i \qquad (3)$$

Secondly, we select the Walker Star Constellation topology for comparison, considering 10 planes with an altitude of 550 km and an inclination of 53 degrees, as most of the Starlink Satellites in orbit.

Finally, we use the database of active satellites in LEO for simulating how the coordination performances of real satellites would improve if we implement different coordination methodology in orbit.

The propagation module provides the position expressed in orbital and cartesian parameters, and the velocity of each node for each time step. These outputs are essential for the following modules; therefore, we validated our values with the propagation of PoliAstro [13], and the resulting relative error is in the order of 10^{-6} on the cartesian coordinates for each time step.

4.2 Imaging Payload Module

The goal of the imaging payload is to observe the target and provide data regarding its position or image, which can then be propagated among the federated satellites. To detect objects in space, we first define the properties of the payload. Each satellite is equipped with an optical imaging system, which, for the purpose of the model, always points in the satellite's velocity direction, with a field of view of 2.22 degrees.

Given a wavelength λ in the upper limit of the visible light of 700 nm, the objects' detectability varies based on their distance d and the aperture diameter D, hence we use formula 4 to evaluate the minimum size of the target object $targer\_size_{min}$.

$$target\_size_{min} = 1.22\frac{d\lambda}{D} \tag{4}$$

For instance, an object further away must be larger than one closer to the satellite to be resolved. In our case, for example, at a distance of 500 km, the smallest size that can be detected is 4.75 m.

4.3 Communication and Data Handling Module

The communication and data handling module ensures the data exchange among the satellites of the federation. It receives the position of the satellites for each time step by the propagation module, then, it evaluates the distance separating the satellites, determines if the communication between two nodes can be guaranteed, and calculates the effective data rate. In this paper, we consider a UHF omnidirectional antenna on board of each satellite, hence, Table 2 shows the parameters of the communication module.

Table 2. Communication Parameters

Communication Parameters	Value	Unit
Transmitting Power	2	W
Receiver Gain	1	dB
Receiver Losses	0.5	dB
Transceiver Gain	1	dB
Transceiver Losses	3	dB
Frequency	437	MHz
Bandwidth	9600	Hz
Symbol Rate	9600	-
Modulation Order	4	-
Sensitivity Receiver	-151	dBW

Communication between satellites is effective only if one of the two satellites communicating at a specific time step possesses the data to be propagated within the federation. The module defines which satellites can communicate with each other, depending on the frequency band and the characteristics of the communication subsystem used.
This module also enables us to evaluate the effective data rate once communication is established. It takes into account Free Space Losses (FLS) and noise levels to calculate the Signal-to-Noise Ratio (SNR). Next, we consider the Ideal Data Rate, which represents the maximum possible data transfer speed, factoring in the Bit-Error-Rate (BER) and the limitations due to symbol rate and modulation order. Using this process, we evaluate the amount of data that can be exchanged during each time step.
Depending on the time of contact and the resulting data rate, different packages of data can be propagated among the satellites. Therefore, we consider various packet sizes. First, we analyze the orbit of an object in space using the two-line element (TLE) format, which represents the position of the detected target in our use case. For end-to-end data communication, we define a suite of telecommunication protocols to ensure that the transmitted data is successfully sent, routed, and interpreted by both the information provider and the receiver. We select Saratoga, based on the UDP protocol developed by Surrey Space Technologies Ltd, as the transport layer protocol [14] . For the network layer, we use Better Approach to Mobile Ad-hoc Networking (BATMAN), developed by the German Freifunk community as a successor of the Optimized Link State Routing Protocol (OLSR) [15]. Additionally, we choose AX.25 as the data link layer protocol, which uses a 32-byte header and a 3-byte trailer appended to the payload [16]. Along with the protocol headers, we add bits from the Reed-Solomon coding scheme to the total message to be transmitted [17]. Table 3 lists the data dimensions for the TLE, taking the layer protocols into account.

Table 3. Data Dimension spread in the network

Data dimension	Values [bytes]
TLE data	104
Transport Layer Protocol	34
Network Layer Protocol	24
Datalink Layer Protocol	35
Encoding Scheme Reed-Solomon	13
TOTAL in bytes	210
TOTAL in bits	1680

We also consider additional packet sizes, recognizing that the network must not only transmit the target's position but also data related to telemetry, detailed information about the detected target, or compressed images. The data to be sent ranges from a single bit to 100,000 bits. In such a scenario, satellites can efficiently share crucial data, ensuring that they operate cohesively as part of a network in the vast expanse of space. We assumed that satellites can exchange the data only if the entire data is sent without interruptions. Once a satellite receives the data, it undergoes a processing time of 1 second before the receiving satellite can forward the information to others. This discussion offers a complete formulation of the model, emphasizing its modules and parameters. It also leads to the presentation of the results of the simulations, highlighting potential enhancements for future investigations.

5. Results

The main results of this framework focus on the time required to spread data among the satellites in the federation. Key highlights of the results include:

1. The time to spread the TLE data as a function of the number of satellites in the SSO federation and Walker Constellation.
2. The time to spread the TLE data as a function of the number of satellites and degree of centrality in Walker Constellation.
3. The time to spread the data in the SSO federation considering different packet sizes.
4. Preliminary results of the time to spread the data among active satellites in LEO.

Through various plots followed by in-depth discussions, we aim to highlight the dynamics of the network and implications of these different coordination techniques, packet sizes, and topology architectures within federation satellite systems.

5.1 Time to spread the TLE data depending on the number of satellites with decentralized coordination in SSO and in a Walker Constellation

First, we analyze the time required to spread the TLE data, corresponding to 1680 bits, among a SSO federation of N_s satellites by varying the number of satellites, randomizing the initial true anomaly and right ascension of ascending nodes. Initially, we assume that only one satellite holds the information that needs to be disseminated.

The satellites of the federation can distribute the data among each other with a decentralized coordination. We evaluate the propagation time for a number of satellites N_s varying from 20 to 10,000. We present results considering 20 iterations of the algorithm, for each number of satellites, for evaluating the mean values and standard deviations. Figure 4 provides a visual representation of the time durations required for information propagation.

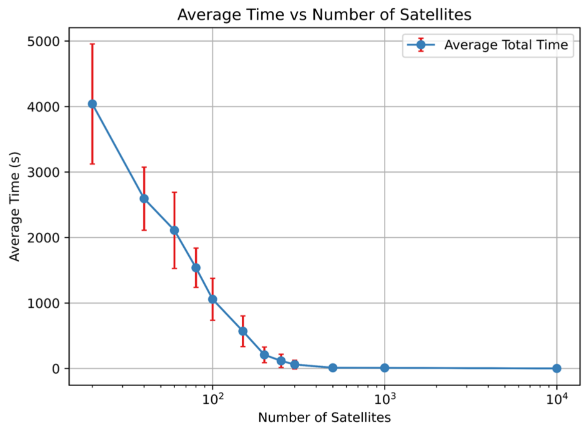

Figure 4. Time to propagate the TLE data among a decentralized SSO federation of N satellites with standard deviations

Fig. 4 shows that the total time to spread information amongst all satellites decreases by increasing the number of satellites in the federation. This phenomenon occurs because the distribution of spacecraft nodes in orbit affects the rate of information exchange. In networks with fewer nodes, the average distance between them is greater, which limits the rate at which information can be exchanged. The initial positions of satellites play a more significant role, as seen in the larger standard deviations found in smaller networks. As the number of nodes increases, the chances of them being within the maximum communication range improve, allowing for more efficient information dissemination. However, once the network reaches a certain size, adding more satellites brings diminishing returns, with minimal effect on the speed of target detection and information spread.

Figure 5 shows a similar pattern, illustrating the average time required to spread TLE data using decentralized coordination in Walker constellations with 10 planes. The plot begins with 60 satellites. The graph shows the average time (in seconds) required to disseminate TLE data across a network of satellites, with the packet size fixed at 1680 bits. The results indicate a clear trend of decreasing coordination time as the number of satellites increases. Initially, for small networks, the average time to spread TLE data is relatively high, peaking at approximately 1230 s. This is expected due to the limited number of nodes available to relay data, which slows the propagation process in the early stages.

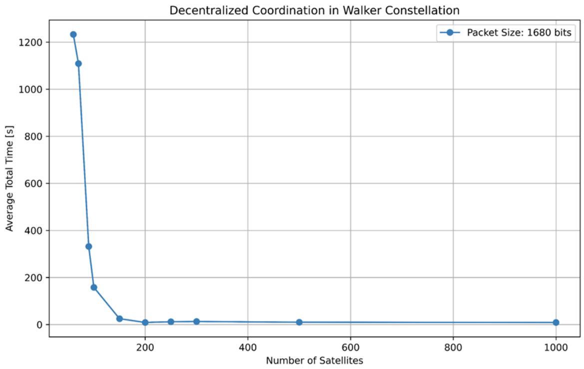

Figure 5. Time to propagate the TLE data among a decentralized Walker federation of N satellites

As the network size grows, the average time drops sharply, reaching below 50 seconds when the network expands to around 150 satellites. This rapid decrease demonstrates the efficiency of decentralized coordination, where each additional satellite in the network increases the number of available communication paths, enabling faster distribution of the TLE data.

After the network size exceeds 200 satellites, the average time stabilizes around 10 seconds or less, even as the number of satellites increases up to 1000. This behavior highlights the scalability of the decentralized coordination model for Walker constellations. Once the network reaches a certain size, the additional nodes primarily serve to reinforce the existing communication paths, rather than significantly reducing latency further.

In comparison to the results in Fig. 4 (SSO constellations), the Walker constellation exhibits more stable performance with larger networks and consistently lower latency once the network grows. This suggests that decentralized coordination in Walker constellations may provide more predictable and uniform performance across a wide range of network sizes, making it a highly effective model for larger constellations, demonstrated by the fact that it is of wide use.

5.2 Time to spread the TLE data depending on the number of satellites and degree of centrality in a Walker Constellation

This section studies the effect of different degrees centrality, hence changing the central nodes, on the diffusion of the Two-Line Elements in a Walker Constellation.

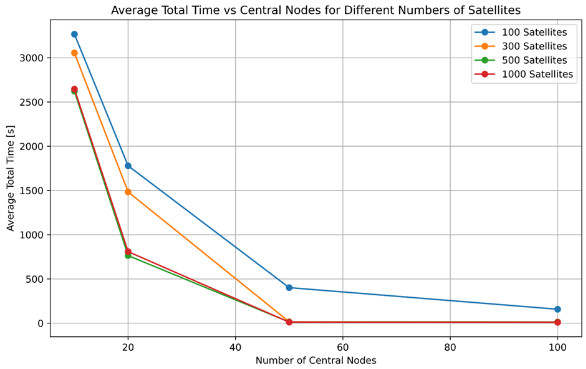

Figure 6. Time to propagate the TLE data among a Walker constellation of N satellites with different central nodes

Fig.6 illustrates the relationship between the average total time and the number of central nodes for satellite constellations of varying sizes. As the number of central nodes increases, the average total time significantly decreases for all constellation sizes, reflecting that the efficiency of spreading the data improves from distributing the network coordination load. The largest reduction in time occurs when the number of central nodes increases from a low number, after which the curve gradually flattens as more central nodes are added. For larger constellations, such as the 1,000-satellite configuration, the total time stabilizes more quickly, indicating that beyond a certain point, adding central nodes provides diminishing returns in terms of reducing the total coordination time. This suggests that while decentralizing the network has a substantial impact, the optimal number of central nodes depends on the constellation size to balance coordination efficiency with system complexity.

5.3 Time to spread the information depending on the packet size in a federation of satellite in SSO

Another outcome of this research is the analysis of the time required to disseminate information across a federation of satellites in Sun-Synchronous Orbit (SSO) as a function of the packet size. This section delves into how the size of the transmitted data impacts the overall efficiency and speed of information propagation within the satellite network.

Fig. 7 illustrates the impact of packet size on the average time required to spread data across a satellite network with decentralized coordination in Sun-Synchronous Orbit (SSO). The x-axis represents the number of satellites in the network, ranging from 0 to 1,000, while the y-axis shows the average time, in seconds, for the network to disseminate the data.

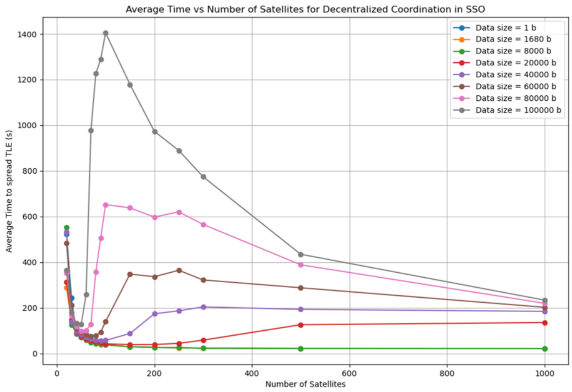

Figure 7. Time to spread different packet sizes in SSO federations of satellite with varying number of satellites

Fig. 7 reveals a strong correlation between packet size and coordination time. For smaller packet sizes (e.g., 1 b and 1680 b), the average time remains relatively constant across all network sizes, demonstrating high efficiency in decentralized coordination even as the number of satellites increases. However, as the packet size increases, the average time to spread larger data initially rises before stabilizing or decreasing as the network scales. For instance, at a packet size of 100,000 b, the average time reaches its peak at around 1,400 seconds when the network consists of approximately 100 satellites. Beyond this point, the time decreases as the number of satellites grows, eventually converging around 200 seconds when the network reaches 1000 satellites. This behavior occurs because larger networks offer more communication channels for distributing data, which compensates for the overhead introduced by larger packet sizes.

5.4 Preliminary results of the time to spread the data among active satellites in LEO.

We conducted another simulation using a database of active satellites in Low Earth Orbit (LEO), simulating a scenario where all satellites share their Two-Line Element (TLE) data in a decentralized manner. These initial results suggest that, with smaller packet sizes such as 1,680 bits (typical for TLEs), the entire network could receive the data in approximately 2 seconds. This quick dissemination indicates the potential efficiency of decentralized coordination in large, real-world satellite constellations, where multiple satellites can relay data simultaneously, minimizing latency.
However, when the packet size increases to 20,000 bits, the average dissemination time extends to around 10 seconds. While this increase is expected due to the larger amount of information that needs to be transmitted, the results still highlight the potential scalability of decentralized systems, even when handling larger data payloads.
It is important to note that these results on the use of active satellites are preliminary, and further research is necessary to validate and refine the findings. The simulations provide an early indication of how decentralized coordination might perform in operational satellite networks, but several factors, such as network congestion, and more complex communication protocols, remain yet unexplored. Future work will involve conducting more comprehensive simulations, testing with different satellite configurations, and analyzing performance under a broader range of operational conditions. These efforts will provide a deeper understanding of the practical limitations and potential of decentralized coordination for large-scale satellite networks.

6. Discussion

The results of this study underscore the significant advantages of decentralized coordination in satellite networks, particularly in managing latency and data dissemination across large federations. A central theme emerging from the analysis is the ability of decentralized systems to efficiently reduce latency, a key challenge for future satellite networks, especially when evolutionary to larger constellations. The study demonstrates that as the number of satellites increases, decentralized coordination offers marked improvements in latency performance compared to centralized methods. By enabling nodes to communicate directly with each other, decentralized architectures eliminate the bottlenecks typical of centralized systems, where communication flows through a single node, creating a potential point of failure. This is particularly important as satellite networks grow in size, complexity, and operational demands.
The size of the data being transmitted plays a crucial role in determining latency. For smaller packet sizes, the decentralized system performs efficiently, regardless of network size, as data propagation happens quickly across all nodes. However, as the size of the data increases, latency naturally grows in smaller networks. Interestingly, beyond a certain threshold, i.e., 100 satellites for a packet size of 100 kb, the latency begins to decrease, even with larger packet sizes, due to the greater number of available communication paths. This demonstrates the scalability of decentralized systems, which maintain efficient performance as the network expands. The decentralized approach is particularly advantageous in larger satellite constellations, where additional nodes enhance communication redundancy and reduce the time required for data propagation, despite the increasing volume of information being shared.

As presented and supported from literature review in Section 2, when comparing centralized and decentralized architectures, the findings show that centralized systems, while easier to implement, struggle to scale efficiently as the network grows. Centralized coordination introduces vulnerabilities such as single points of failure, requiring higher communication bandwidth particularly for larger satellite federations. In contrast, decentralized coordination distributes the decision-making process across multiple nodes, enhancing the system's robustness, removing the reliance on a single central node, and it enhances the connectivity of the network. To support the presented related works, the results of this study also highlight the influence of the number of central nodes on overall network performance. Increasing the number of central nodes and moving towards more decentralized networks leads to a significant reduction in latency across all satellite constellations.

The study also explores the performance of different satellite constellations, with a particular focus on Sun-Synchronous Orbit (SSO) and Walker constellations. Both constellations show significant improvements in latency under decentralized coordination, particularly as the number of satellites increased. However, Walker constellations demonstrate more stable performance in larger networks, with consistently lower latency once the satellite count surpassed 200. This suggests that decentralized coordination in Walker constellations offers a more predictable and uniform performance across a wide range of network sizes, making it a highly effective model for larger constellations. The stability and lower latency observed in Walker constellations further underscore the benefits of decentralized coordination in efficiently managing large-scale networks.

Preliminary findings from simulations using active satellites in Low Earth Orbit (LEO) reinforce the scalability and efficiency of decentralized coordination, as discussed in Section 5.4. Even with small datasets such as Two-Line Element (TLE) data, the decentralized network can disseminate information across the entire constellation in just a few seconds. Larger datasets naturally require more time, but the results still highlight the potential of decentralized systems to handle real-world large-scale satellite networks. This is particularly relevant in the context of future mega-constellations, where decentralized coordination could provide a robust and scalable solution for managing complex, data-intensive satellite operations.

The results of this study clearly demonstrate that decentralized coordination is highly effective for reducing latency in satellite networks, particularly as the number of satellites increases.

7. Future Work

While this research provides valuable insights into decentralized coordination for satellite networks, several areas warrant further investigation. Future studies could focus on refinement of the simulation model, incorporating more complex communication disruptions and network congestion scenarios. This would enable a more detailed analysis of how decentralized systems perform in real-world environments, where external factors may affect communication.

Another aspect for future research is the exploration of hybrid coordination models, which combine both centralized and decentralized elements, where we expect to find the optimum in managing spacecraft operations. Such models could offer the benefits of decentralized communication, while still retaining some of the control and simplicity of centralized systems for specific mission-critical tasks. Investigating how these hybrid systems perform across various network sizes and packet sizes would provide valuable insights for designing more robust and flexible satellite constellations. Lastly, real-world testing and validation of the proposed decentralized coordination strategies would give more insights on ways to improve and analyze the proposed study. Indeed, these findings emphasize the potential of decentralized coordination in managing complex, data-heavy satellite networks, especially in future large-scale constellations, making them a promising approach for future space operations, where autonomy, robustness, and quick data dissemination are essential for success.

8. Conclusion

This study presents a comprehensive evaluation of latency optimization in centralized and decentralized coordination for time-varying evolutionary satellite networks. The findings demonstrate that decentralized coordination offers significant advantages over centralized approaches, particularly in terms of time to spread different packet sizes among the nodes of a federation of satellites. As satellite constellations continue to grow in size and complexity, decentralized systems will be crucial in mitigating the limitations of centralized architectures, such as single points of failure and bandwidth constraints. The study further highlights that decentralized coordination becomes increasingly efficient as the number of satellites in a network rises, offering more communication pathways and enabling faster data dissemination, even as packet sizes grow.

Another key conclusion is the relation between packet size and latency. While smaller datasets are transmitted quickly in both small and large networks, larger datasets initially face increased latency in smaller networks. However, as networks expand beyond a critical threshold, decentralized architectures effectively reduce this latency, demonstrating their scalability and flexibility. This makes decentralized coordination particularly suitable for large satellite constellations, which require efficient and resilient communication systems.

The comparison between Sun-Synchronous Orbit (SSO) and Walker constellations revealed that decentralized coordination is effective across different network topologies, though Walker constellations showed more stable performance in larger networks. These findings underscore the potential of decentralized systems to support the next generation of satellite networks, particularly in mega-constellations and other large-scale satellite operations.

References

[1] G. Palermo, A. Golkar, and P. Gaudenzi, "Earth Orbiting Support Systems for commercial low Earth orbit data relay: Assessing architectures through tradespace exploration," *Acta Astronaut*, vol. 111, pp. 48–60, 2015, doi: 10.1016/j.actaastro.2015.02.011.

[2] D. Arnas, M. Lifson, R. Linares, and M. E. Avendaño, "Definition of Low Earth Orbit slotting architectures using 2D lattice flower constellations," *Advances in Space Research*, vol. 67, no. 11, pp. 3696–3711, Jun. 2021, doi: 10.1016/j.asr.2020.04.021.

[3] A. Golkar and I. Lluch I Cruz, "The Federated Satellite Systems paradigm: Concept and business case evaluation," *Acta Astronaut*, vol. 111, pp. 230–248, 2015, doi: 10.1016/j.actaastro.2015.02.009.

[4] A. Golkar, " Federated satellite systems (FSS): a vision towards an innovation in space systems design," *IAA Symposium on Small Satellites for Earth Observation.* , 2013.

[5] V. Messina and A. Golkar, "Initial formulation of a time varying dynamic graph decentralized optimization framework for scaled satellite network infrastructure operations", 2023.

[6] V. et al. Shah, "Scheduling the world's largest earth-observing fleet of medium-resolution imaging satellites.," in *International Workshop on Planning and Scheduling for Space.*, Berkeley, CA, 2019.

[7] S. Nag, A. S. Li, and J. H. Merrick, "Scheduling algorithms for rapid imaging using agile Cubesat constellations," *Advances in Space Research*, vol. 61, no. 3, pp. 891–913, Feb. 2018, doi: 10.1016/j.asr.2017.11.010.

[8] J. Boerkoel, J. Mason, D. Wang, S. Chien, and A. Maillard, "An Efficient Approach for Scheduling Imaging Tasks Across a Fleet of Satellites." [Online]. Available: http://modis.higp.hawaii.edu/

[9] S. Phillips and F. Parra, "A Case Study on Auction-Based Task Allocation Algorithms in Multi-Satellite Systems," in *AIAA Scitech 2021 Forum*, Reston, Virginia: American Institute of Aeronautics and Astronautics, Jan. 2021. doi: 10.2514/6.2021-0185.

[10] C. T. Grégory Bonnet, "Multi-Agent Collaboration: A Satellite Constellation Case," in *Frontiers in Artificial Intelligence and Applications*, vol. Vol 179: STAIRS 2008, 2008.

[11] I. Zilberstein, A. Rao, M. Salis, and S. Chien, "Decentralized, Decomposition-Based Observation Scheduling for a Large-Scale Satellite Constellation," 2024. [Online]. Available: www.aaai.org

[12] S. Parjan and S. A. Chien, "Decentralized Observation Allocation for a Large-Scale Constellation," *Journal of Aerospace Information Systems*, vol. 20, no. 8, pp. 447–461, Aug. 2023, doi: 10.2514/1.I011215.

[13] Juan Luis Cano Rodríguez et al., "poliastro/poliastro: poliastro 0.17.0 (SciPy US '22 edition) (v0.17.0)."

[14] W. E. C. S. W. I. C. J. Lloyd Wood, "Saratoga: A Scalable Data Transfer Protocol. Internet-Draft draft-woodtsvwg- saratoga-22, Internet Engineering Task Force," 2017.

[15] R. Sanchez-Iborra, M.-D. Cano, and J. Garcia-Haro, "Performance Evaluation of BATMAN Routing Protocol for VoIP Services: A QoE Perspective," *IEEE Trans Wirel Commun*, vol. 13, no. 9, pp. 4947–4958, Sep. 2014, doi: 10.1109/TWC.2014.2321576.

[16] Tucson Amateur Packet Radio, "AX.25 Link Access Protocol for Amateur Packet Radio, Version 2.2,"."

[17] S. Scrocciolani, V. Messina, R. M. G. Alarcia, J. Sindermann, and A. Golkar, "Advancing Satellite Network Performance: Network Analysis for Federated Satellite Systems," *IEEE Access*, vol. 12, pp. 45616–45630, 2024, doi: 10.1109/ACCESS.2024.3378743.