



The Role of Central Nodes in Multi-Task Allocation for Distributed Space-Based Observation Systems

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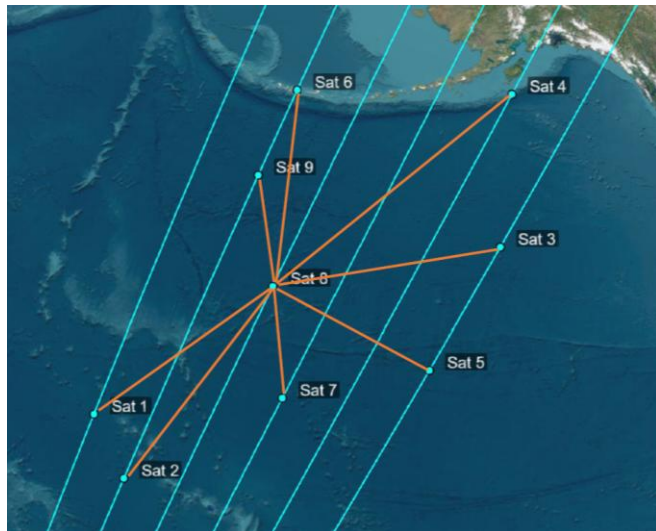
Beyond the “Centralized vs Decentralized” Extremes

Distributed Satellite Systems (DSS) are typically studied at the two extremes of the coordination spectrum.



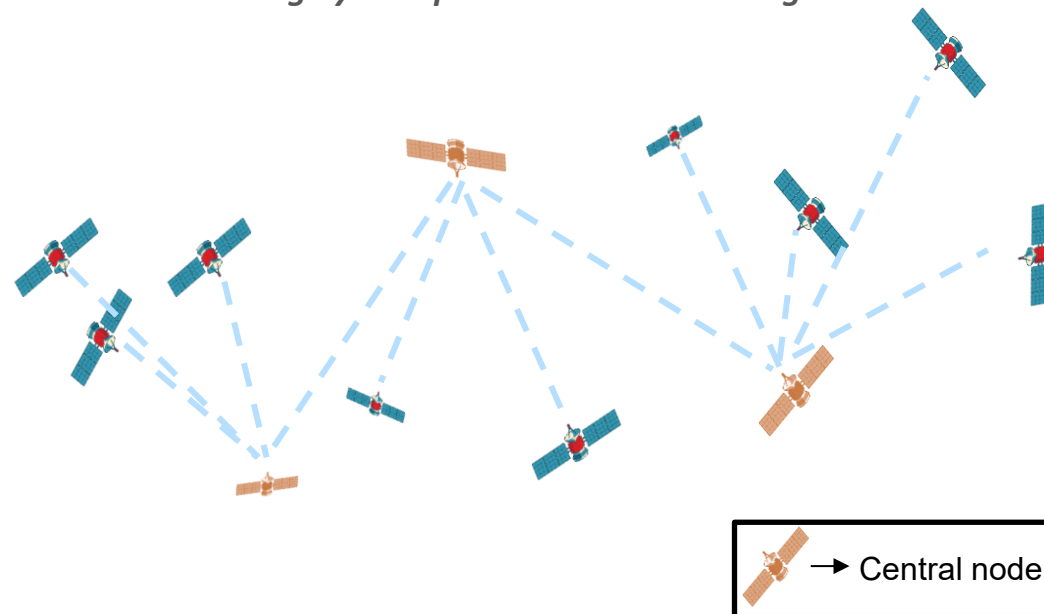
FULLY CENTRALIZED

Single point of failure
Doesn't scale



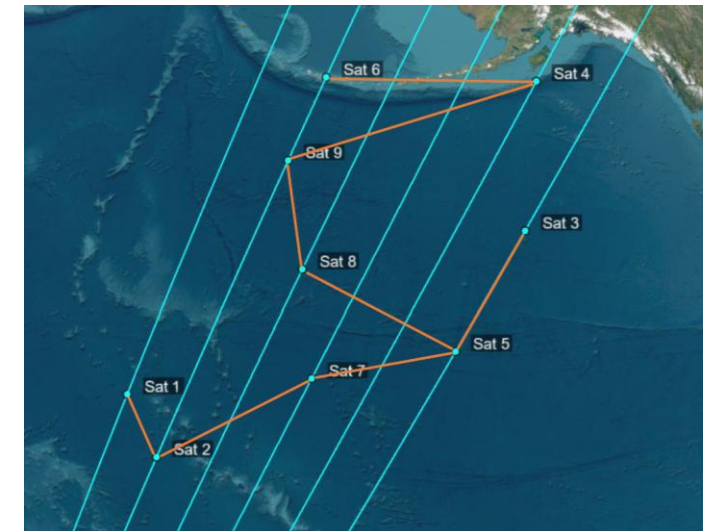
PARTIAL CENTRALIZATION

Largely unexplored intermediate regime



FULLY DECENTRALIZED

Costly consensus
Communication Overhead



Comparison of Decentralized Satellite Task Allocation Methods

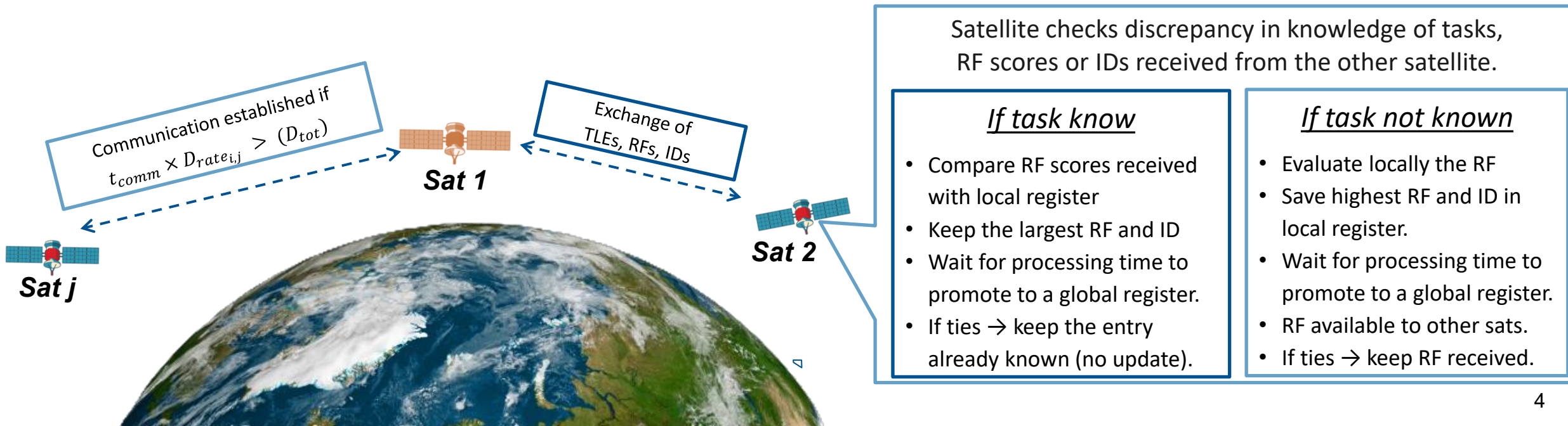
	BD [1]	NSS/DCOP [2]	m-ACCBA [3]	RF Selective Prop. (Proposed)
Approach	Broadcast satisfaction	Decomposition & stochastic search	Auction-based bidding	Reward-based selective propagation
Communication	Broadcast — high volume	Scoped to neighborhood	Quadratic in task count	Reduced: rewards, IDs, timestamps
Computation	Light — simple heuristics	Moderate — local search	Heavy — all permutations	Light — reward prediction only
Scalability	Medium–High	High	Limited	Very High (1000s of sats)
Network Topology	Static	Static (Mostly)	Static (Mostly)	Dynamic — orbital dynamics
Satellite Knowledge	Local heuristics	Neighbors only	Unknown	Local + RF only
Task Knowledge at Init	Global	Global	Global	Single sat only — propagates
Central Node Study	Not studied	Not studied	Not studied	Different degrees analyzed

*to the best of my knowledge

Objectives and RF-Selective Propagation

Main Objective: Quantify how the **fraction of central nodes** shapes the performance of multi-task allocation in Distributed Satellite Systems, across the **full centrality spectrum**.

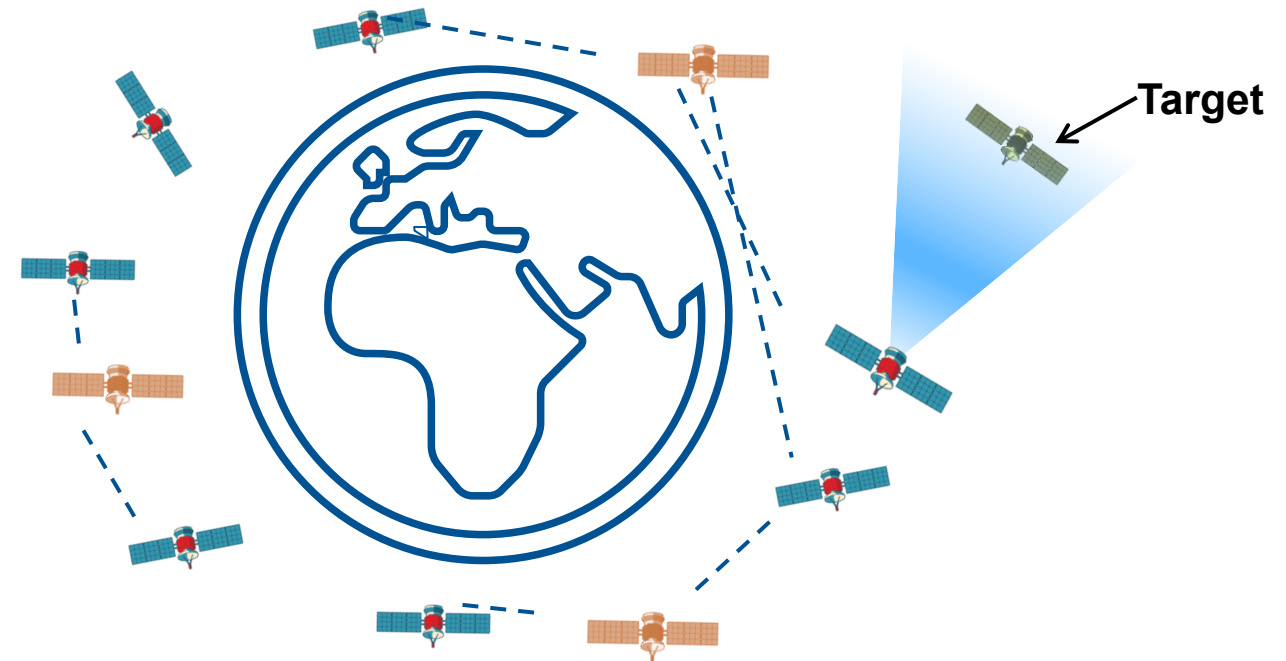
Secondary Objective: Extension of the single-task selective propagation framework [4] to a multi-task reward function based selective propagation framework.



Problem Formulation – Use Case

We study the problem of **allocating multiple observation tasks** of target objects in SSO orbits, among a satellite in a Walker-Delta constellation, varying the fraction of central nodes.

- Satellites share only TLEs of targets, best known RFs and IDs
- Only one satellite initially knows the full task set. Tasks must propagate through the network.
- Tasks are distributed among the satellites in parallel to the bidding. Allocation must converge to a unique best-bidder per task.
- Each satellite is unaware of the presence of other satellites and their capabilities before communicating.
- Satellites have limited resources and computational capabilities.



Problem Formulation – Use Case

Architectural Design Variables

Tier	Variable	Values
Primary	Fraction of Central Nodes	0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1.0
Secondary	Number of Satellites	100, 500, 1000, 2000, 3000, 5000
Secondary	Number of Target Objects	1, 5, 10, 50, 100, 500



Figures of Merit (FoM)

Name	Description
Time to Converge	Time for one sat to become aware of being best for each task
Task Intensity	Ratio num. tasks n_T / num. satellites n_s Representing the load level of the network
Max Reward Function	Highest performance achieved in a task assignment
Link Efficiency	Ratio of total links n_L before convergence to tasks n_T
Diffusion Time	Time until all sats hold the full task set T ($t_D \leq t_c$)

Reward Function

A scalar score that captures how well a satellite i can perform a given observation task k at time t .

$$RF_i^k(t) = q_i a_i(t) \left[A * p_i(t) + B * d_i(t) + C * \left(1 - \left| \frac{\varphi_i^k(t)}{FoV_i} \right| \right) \right]$$



q Availability of instrumentation {0,1}



a Availability of schedule {0,1}



p

Energy fraction

$$p = E_a / E_{max}$$

Stored energy available for the task



d

Data storage fraction

$$d = DS_a / DS_{max}$$

Available storage memory



φ

Angular proximity

$$1 - \left| \varphi / FoV \right|$$

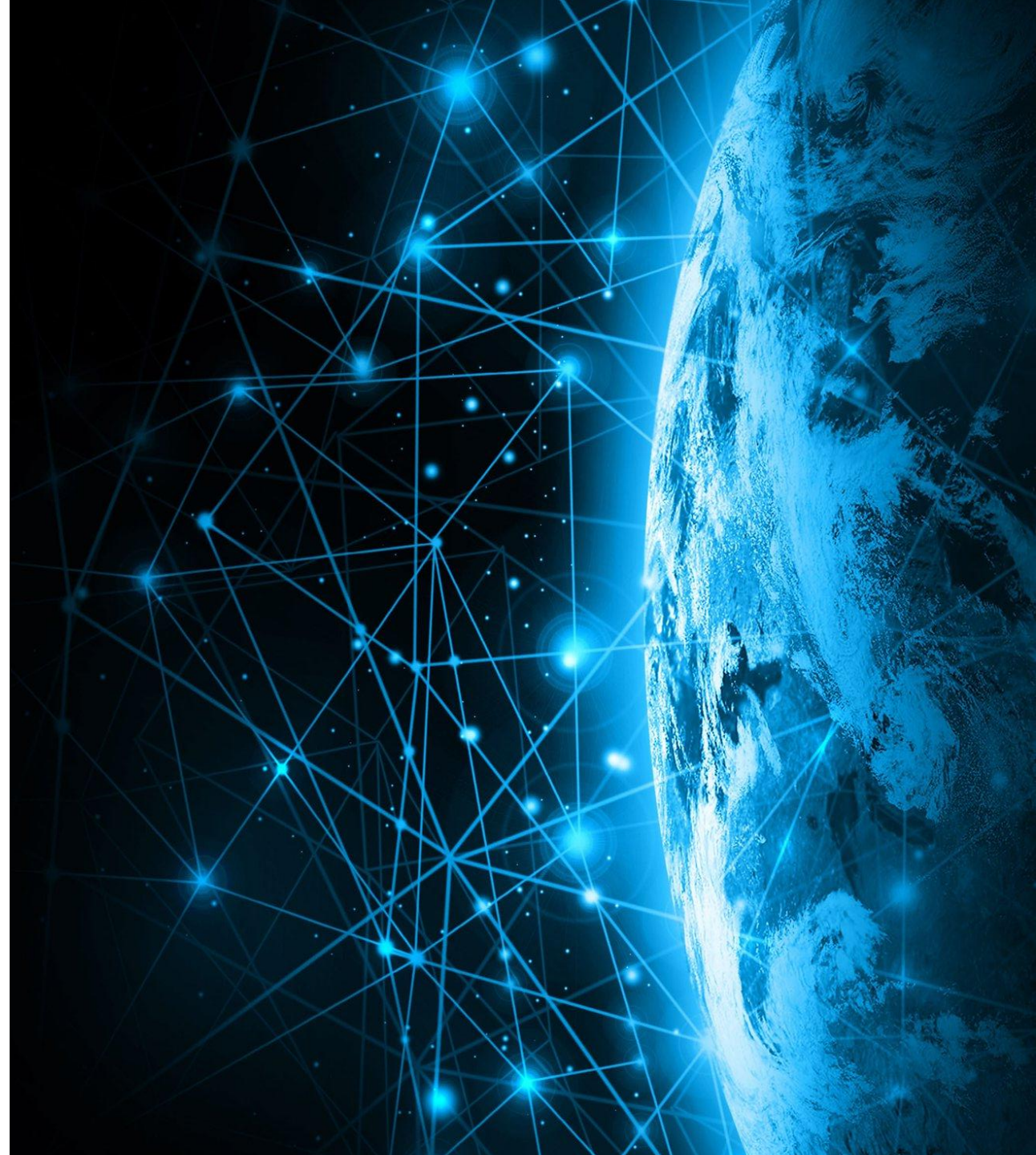
Alignment of payload with target

$A, B,$ and C are scaling factors. The mathematical maximum value is **3.0** in the analyzed case.



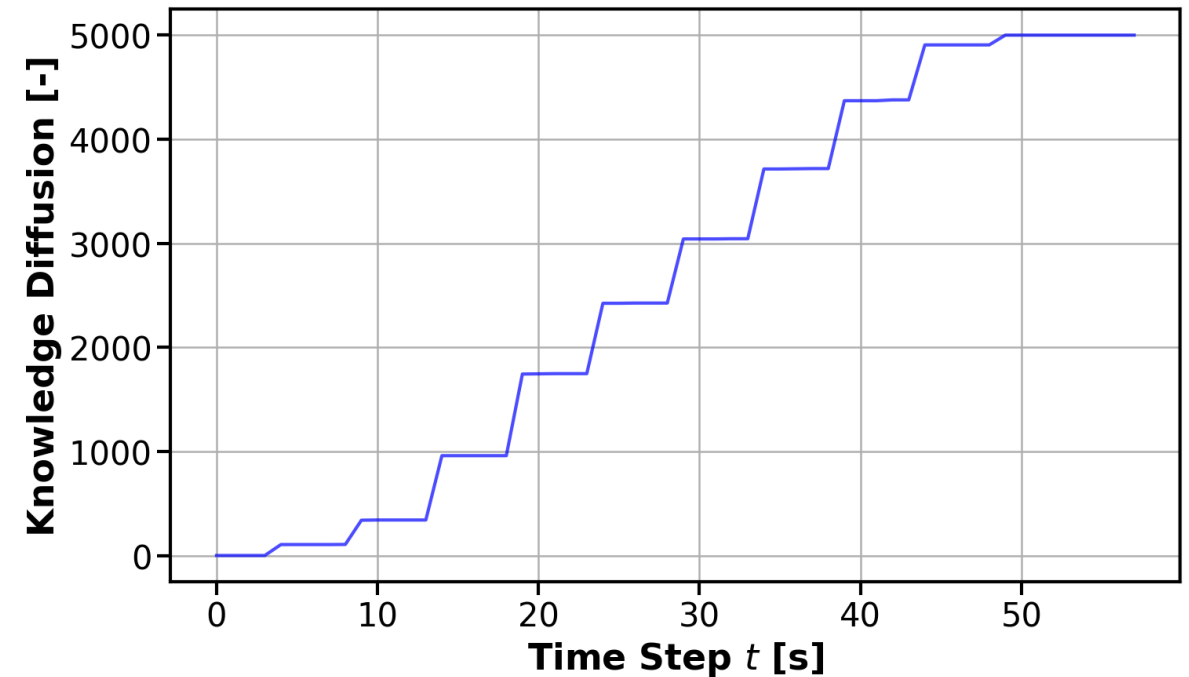
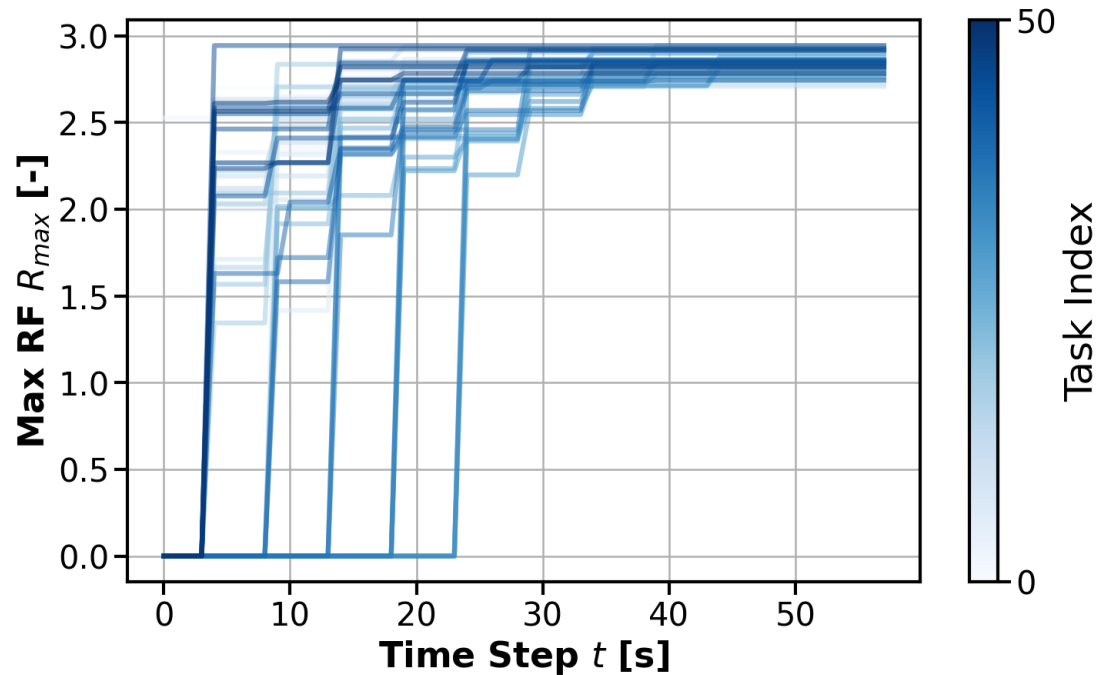
Results

Reward evolution · Knowledge diffusion
Bidding dynamics · Performance landscape
Scale dependence · Power law



Reward Evolution & Knowledge Diffusion

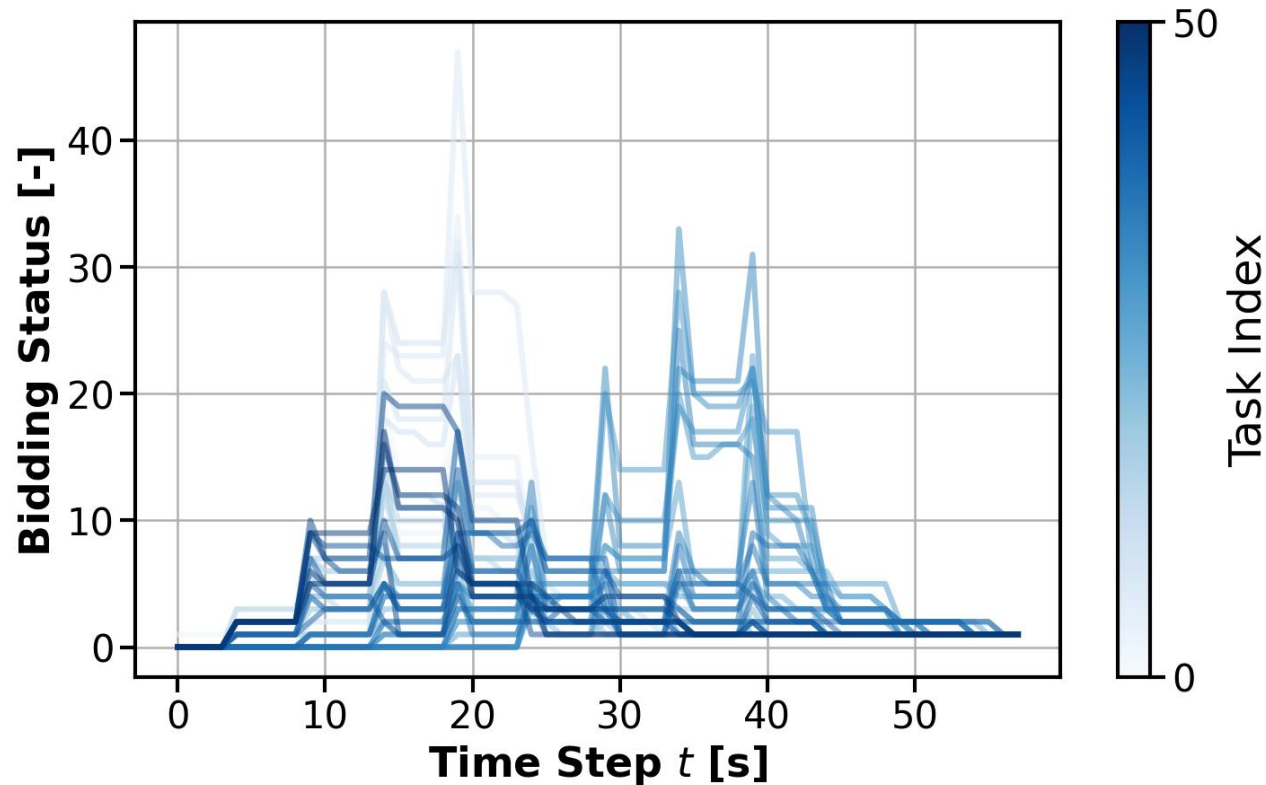
Single run · 5,000 satellites · 50 tasks · 10% central nodes



➔ **75 % of ideal RF reached in 5 s. Full diffusion at $t_D = 48$ s — only 10 s before global convergence. Knowledge diffusion, *not bidding*, is the bottleneck.**

Bidding Dynamics

Number of active candidate bidders per task over time



Initial rise · Task propagates, candidates accumulate.

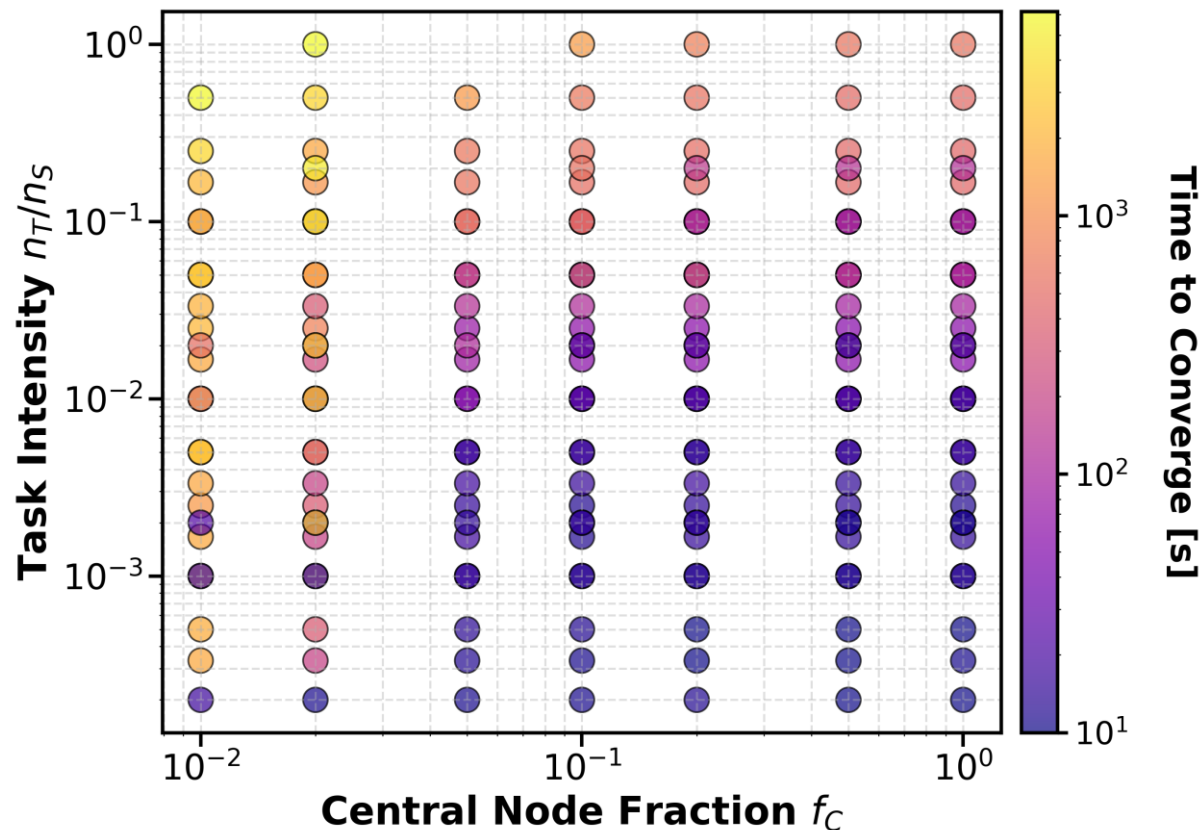
Peak ~40+ · Many candidates competing.

Collapse to 1 · Consensus reached. One winner per task.

➔ Full network convergence in under 60 s across 5,000 satellites coordinating 50 concurrent tasks.

Performance Landscape Across Architectures

Convergence time as a function of central-node fraction and task intensity



$\geq 5\%$

central nodes are enough
to maintain $t_c < 100$ s across all task loads

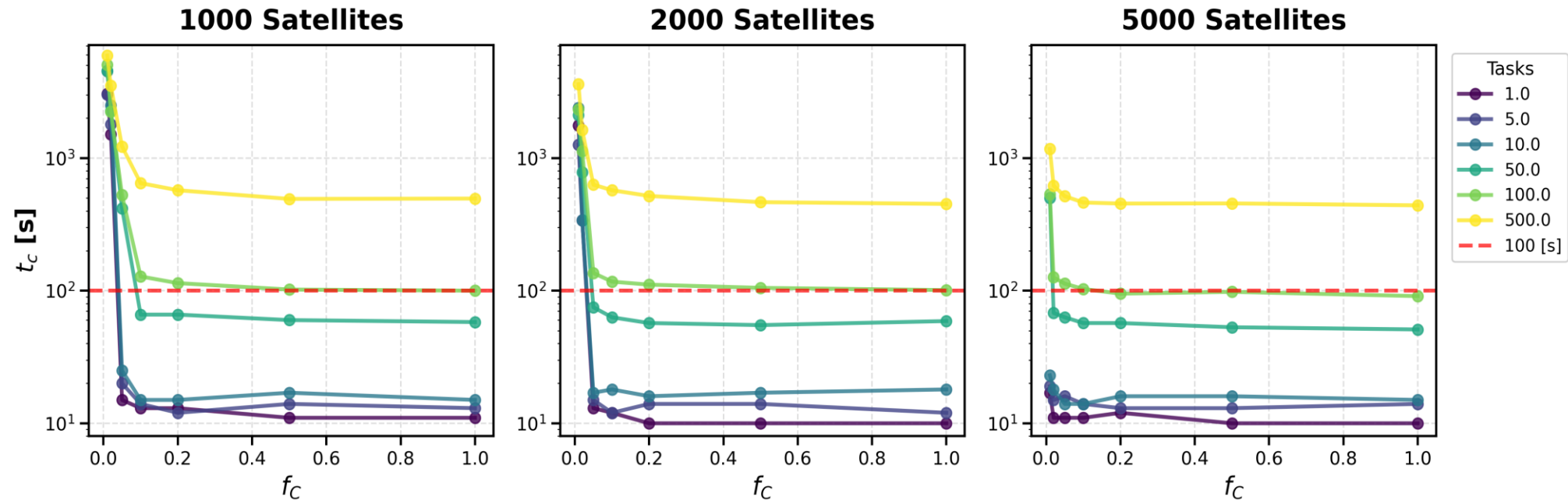
Purple = fast convergence

Yellow = slow / unconverged

Top-left (few CNs, many tasks) is the difficult regime.

Saturation & Scale Dependence

Convergence time vs central-node fraction across three constellation sizes



Saturation

Beyond $f_{CN} \approx 0.10$, additional central nodes yield diminishing returns on convergence time.

Scale effect

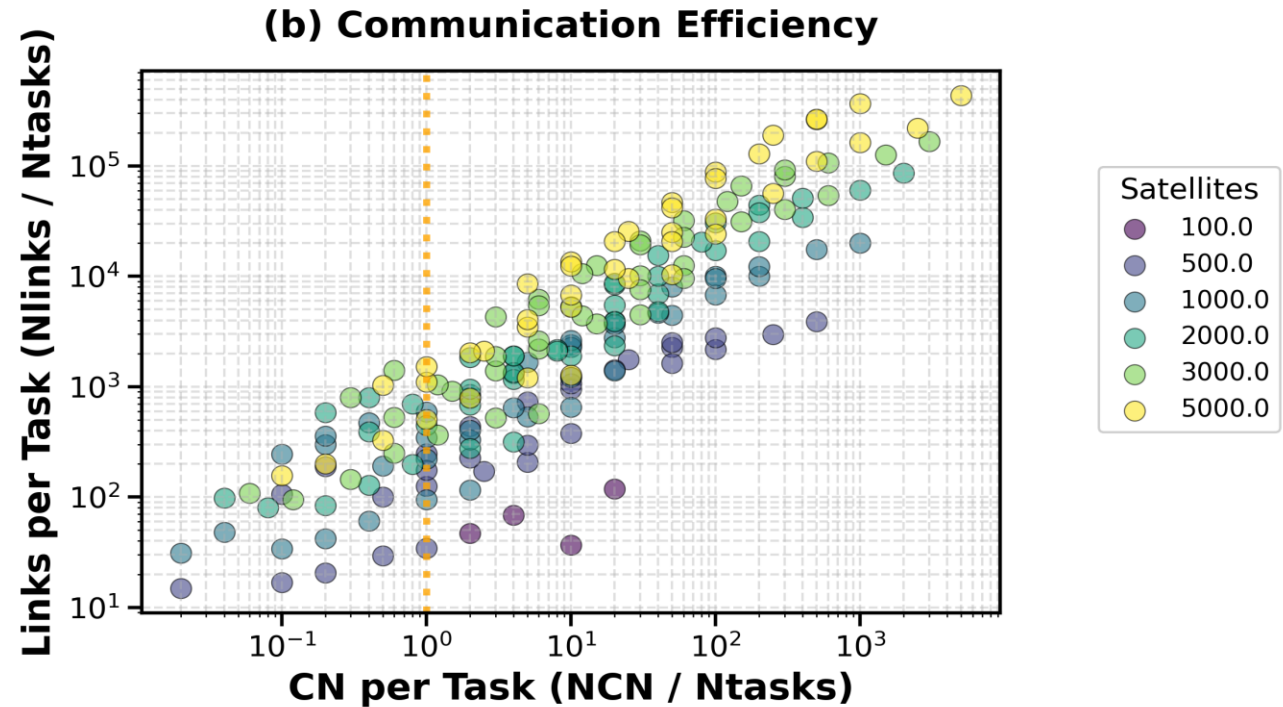
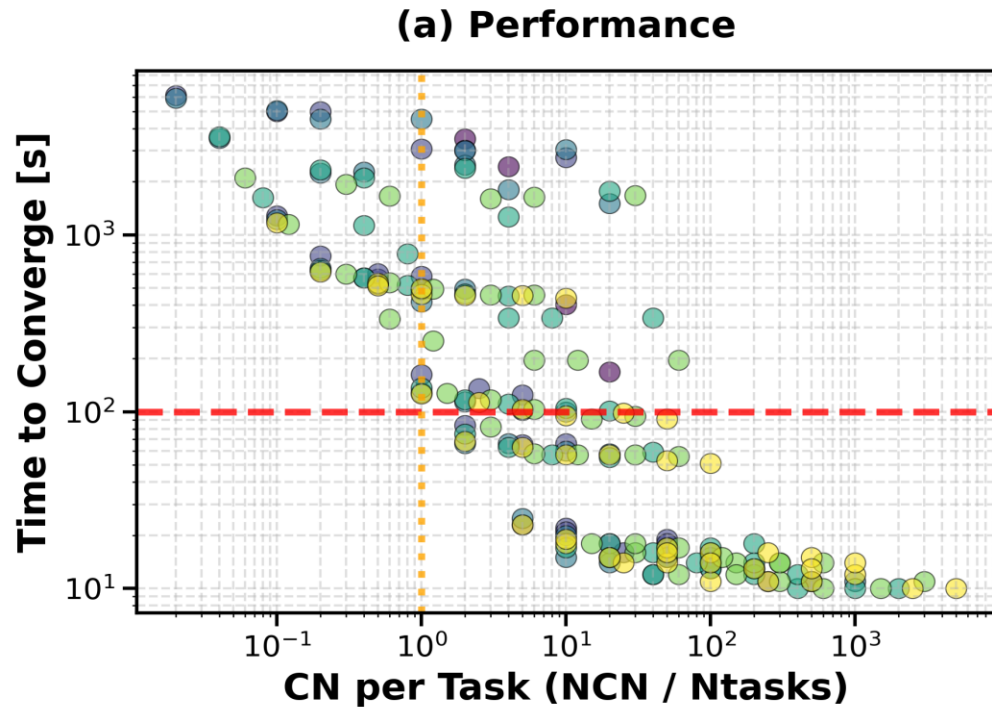
Larger constellations reach the minimum t_c at smaller values of f_{CN} .

Absolute count

Responsiveness is driven by the absolute number of central nodes.

A Scale-Independent Threshold

Time to converge & link efficiency vs n_{CN} / n_T



$n_{CN} \geq n_T$

At least one CN per task
Scale-independent across 100 → 5,000 sats.

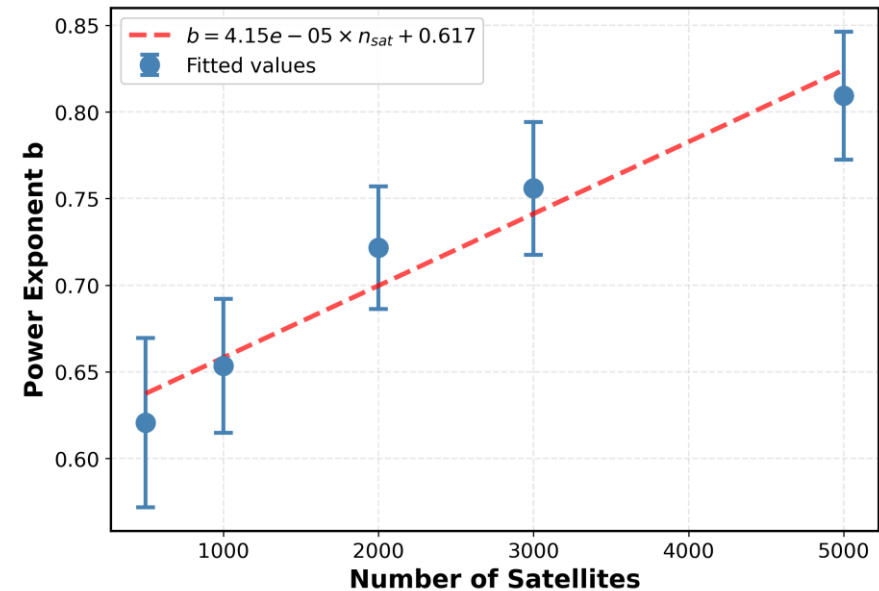
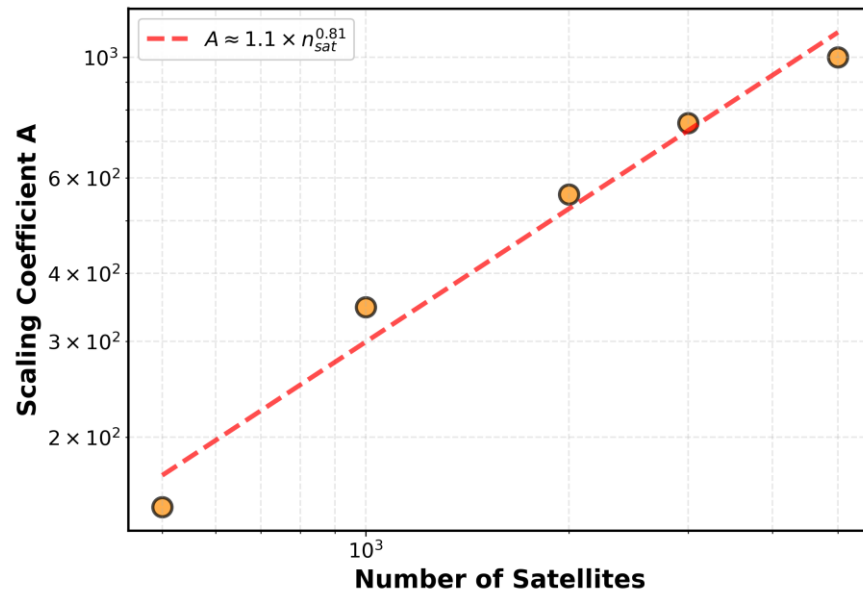
Power Law – Link efficiency

$$\eta_L = A \cdot \left(n_{CN} / n_T \right)^b$$

$$A \approx 1.1 \cdot n_S^{0.81}$$

$$b = 4.15 \cdot 10^{-5} \cdot n_S + 0.617$$

Coefficients scale systematically with constellation size.



Future Work

Already in progress:

- **Resilience analysis:** study network behavior under random and targeted central-node failures.
- **Dynamic task generation:** relax the single-origin assumption with multiple simultaneous task injection points.
- **Optimal CN placement:** determine the best central-node distribution for specific use cases like wildfire detection and planetary boundary layer monitoring.
- **Hardware-in-the-loop:** validate the framework with physical CubeSat communication prototypes.
- **Multi-Objective optimization**, maximizing number of observations and task allocated while minimizing communication links and complexity for Perturbation of the Boundary Layer monitoring, wildfire monitoring and flood monitoring.

For the future-future:

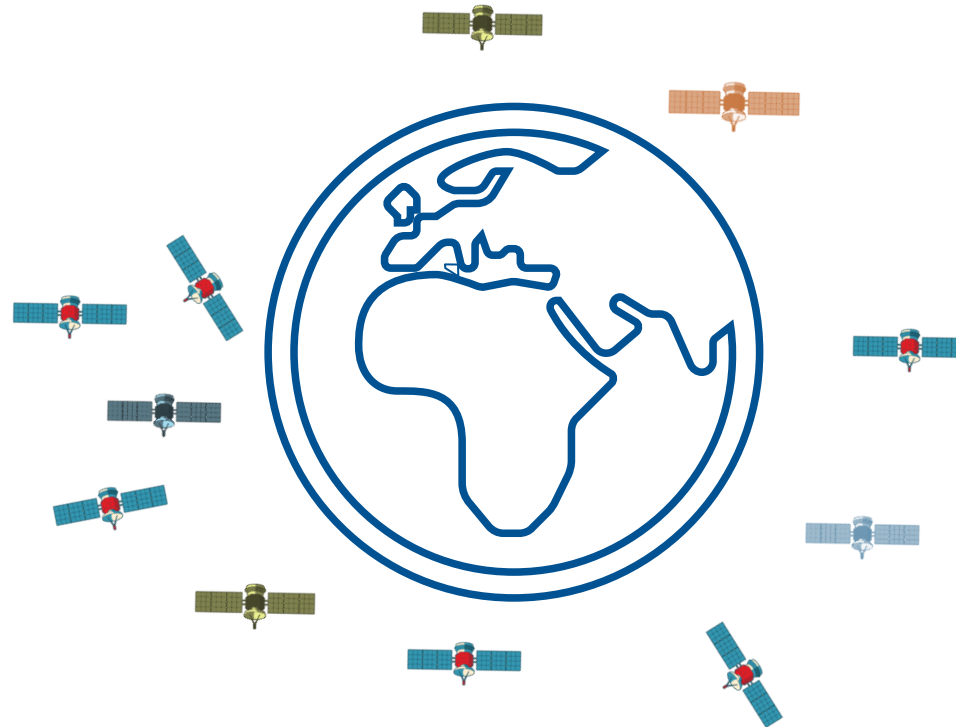
- **Consider more realistic network protocols:** incorporate full inter-satellite communication protocols to improve simulation fidelity.

Conclusion

Reward-based selective propagation scales

Convergence under 100 s for 5,000 satellites and 500 concurrent tasks.

Knowledge diffusion and not bidding is the dominant **bottleneck** under realistic communication constraints.



Results show superior efficiency for hybrid architectures with **only ~5 % central nodes in networks up to 5,000 satellites.**

A **power-law design rule connects link efficiency with the n_{CN} / n_T ratio**, providing a concrete sizing tool for architects.



References

1. Parjan, S.; and Chien, S. A. 2023. Decentralized observation allocation for a large-scale constellation. *Journal of Aerospace Information Systems*, 20(8): 447–461.
2. Zilberstein, I.; Rao, A.; Salis, M.; and Chien, S. 2025. Decentralized, decomposition-based observation scheduling for a large-scale satellite constellation. *Journal of Artificial Intelligence Research*, 82: 169–208.
3. Li, G. 2020. Online scheduling of distributed Earth observation satellite system under rigid communication constraints. *Advances in Space Research*, 65(11): 2475–2496.
4. V. Messina, A. Golkar, "Efficient and Responsive Task Allocation in Distributed Satellite Systems: The Role of Central Nodes", Fourteenth International Workshop on Planning & Scheduling for Space (IWSPSS), 2025.



Thank you for the attention

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Orbital Parameters

Table 4: Orbital Parameters for Satellites and Targets

<i>Variable</i>	<i>Satellites</i>	<i>Targets</i>
Type	Walker Delta	SSO
n_p [-]	10	n_T
a [km]	6923	7171
i [°]	53	98.55 ± 10
e [-]	0	0.0009
Ω [°]	[0, 360]	267
ω [°]	0	84
θ [°]	[0, 360]	[0, 360]

First shell of Starlink
as reference

Envisat and orbits with
higher density of
satellites and debris

The initial true anomaly θ and the right ascension of the ascending node Ω take variable values, given the total number of satellites n_s , satellite i is assigned Ω_i and θ_i according to the equations:

$$\Omega_i = \frac{2\pi}{n_p} \left\lfloor \frac{i}{n_s/n_p} \right\rfloor,$$

$$\theta_i = \frac{2\pi}{n_s/n_p} \left(i \bmod \frac{n_s}{n_p} \right).$$

Data size considered

1. Message to be sent (ID + RF + Object TLE)

Data size	Values [Bytes]
TLE object detected	104
ID + RF	8
Transport Layer Protocol	34
Network Layer Protocol	24
Datalink Layer Protocol	35
Encoding Scheme Reed-Solomon	13
TOTAL	210

1. Power and Data Handling Parameters

Maximum Energy Storage	84 Wh
Power in sunlit	20 W
Power in eclipse	5 W
Solar panel sizes	0.12 m ²
Solar panel packing factor	0.9
Solar panel efficiency	22%
Sun flux	1,370 W/m ²
Maximum data storage	8 GB

1. S. Scroccioli, V. Messina, R. M. G. Alarcia, J. Sindermann and A. Golkar, "Advancing Satellite Network Performance: Network Analysis for Federated Satellite Systems," in IEEE Access, vol. 12, pp. 45616-45630, 2024, doi: 10.1109/ACCESS.2024.3378743.
2. <https://www.e-navigation.nl/content/network-orbit-data>
3. <https://planet4589.org/space/xtle.html>

Communication subsystem - UHF

- UHF omnidirectional antennas
- Max Data Rate: 19200 bits/sec
- This includes the evaluation of:
 - Free Space Losses
 - Antenna Noise
 - SNR
 - Bit-Error-Rate
 - Effective Data Rate

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

Future Work

Testing with hardware.

Setup component:

- Raspberry Pis 5
- nRF24L01 – 2.4GHz RF Transceiver module

