NCA 2025, The 23rd IEEE International Symposium on Network Computing and Applications
November 5-7th, 2025
Instituto Superior Técnico, Lisbon, Portugal

November, 6th 2025

Geometric Swarm Flocking with OWC Constraints

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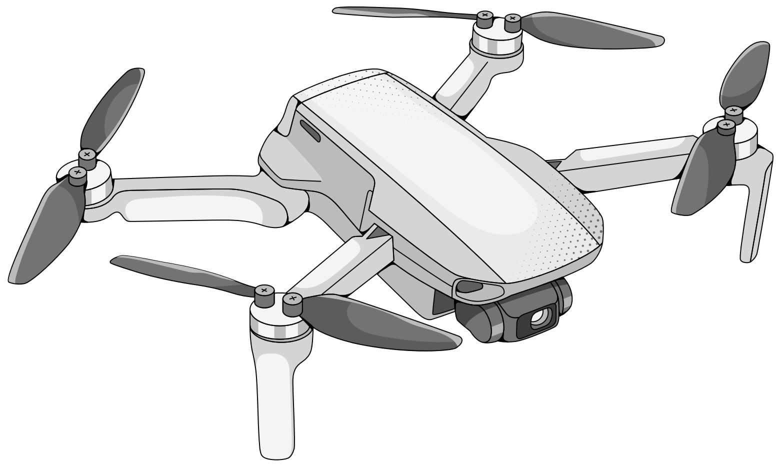
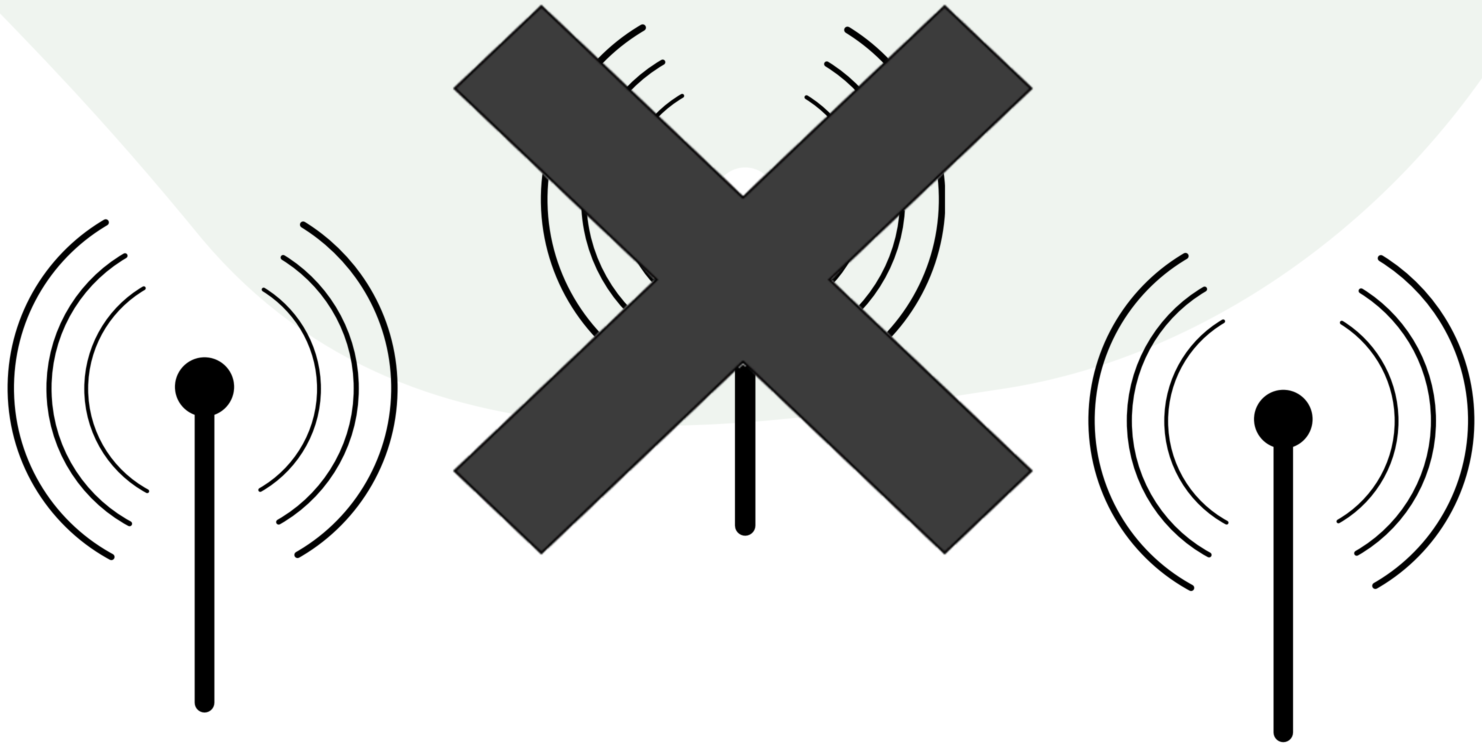
Summary

- Motivation & Background
- Unified Framework
- Leader Election Algorithm
- Simulation & Results
- Future Work & Conclusion

Motivation & Background

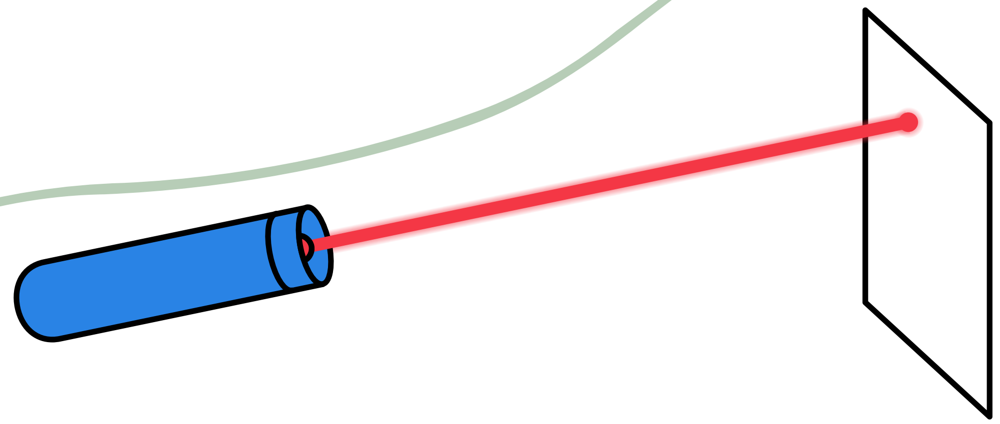
- Swarm robotics enables scalable exploration, monitoring and rescue using aunomous UAVs





- RF communication faces interference, jamming and bandwidth saturation

- OWC (visible-light and laser-based systems) offers high-througput, short-range, line-of-sight channels immunie to RF congestion



Objectives & Main contributions

No existing model simultaneously addresses flocking, leader election and OWC communication in one framework → Our final goal

Main Contributions:

- Multi-criteria local scoring function integration compactness, neighborhood size, target distance and angular dispersion
- Distributed leader election and conflict resolution
- Follower assignment and stabilization yielding coherent sub-swarms without central control
- Large-scale validation up to 5000 UAVs showing scalable coverage and minimal message overhead

Unified Framework

Framework definition & Assumptions :

- UAVs operate in a bounded 2D environment under OWC constraints
- Each UAV acts as an autonomous agent with local sensing and laser diode communication.
- Coordination emerges only from local interactions → no global knowledge or central control.

UAV Model

- Each UAV maintains ID, position, leadership score, and leader assignment.
- Sensing based on LiDAR-like with 360° awareness, 20m range
- Communication based on AO-ODFM laser diode transceivers but line-of-sight only

Leadership score

$$S = \alpha \cdot C + \beta \cdot N + \gamma \cdot D + \delta \cdot A$$

- C(u) : Compactness

$$C(u) = \frac{1}{1 + \sum_{v \in N(u)} e^{-\frac{d(u,v)^2}{\sigma^2}}}$$

- N(u) : Neigbhorhood size

$$N(u) = e^{-\frac{(|N(u)|-\mu)^2}{2\sigma_N^2}}$$

- D(u) : Proximity to target

$$D(u) = 1 - \min\left(\frac{d(u,T)}{d_{\max}}, 1.0\right)$$

- A(u) : Angular dispersion

$$A(u) = \left\| \frac{1}{|N(u)|} \sum_{v \in N(u)} (\cos\theta_{uv}, \sin\theta_{uv}) \right\|$$

α, β, γ, δ are weights for each factors

Election Process

Local UAV algorithm

1. **Initial Proposal** : Each UAV broadcasts its score; local maxima become leader candidates
2. **Conflict Resolution:** Local leader candidates compare score; weaker ones withdraw
3. **Follower Assignment:** Non-leader attach to the best neighboring leader

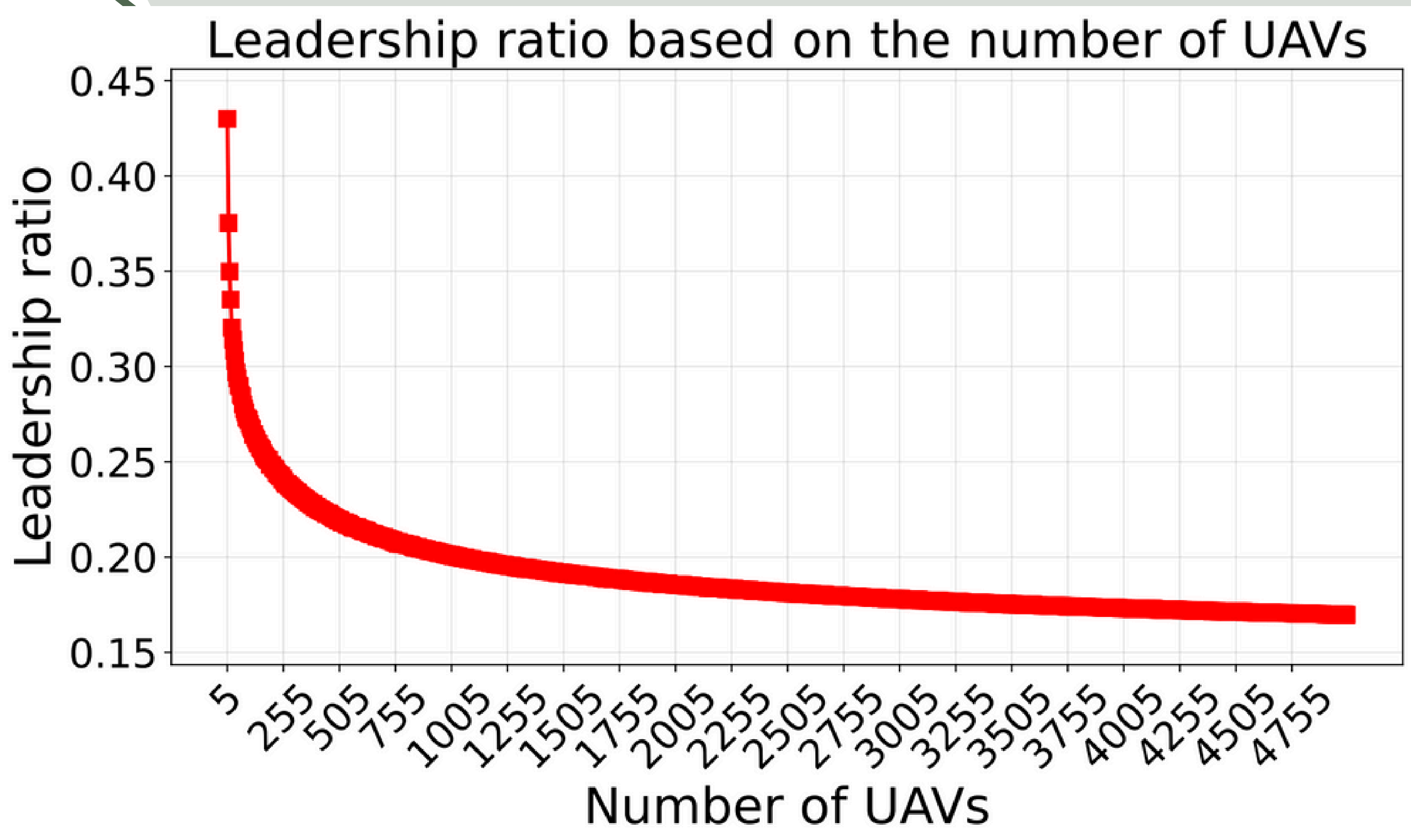
Simulation Setup :

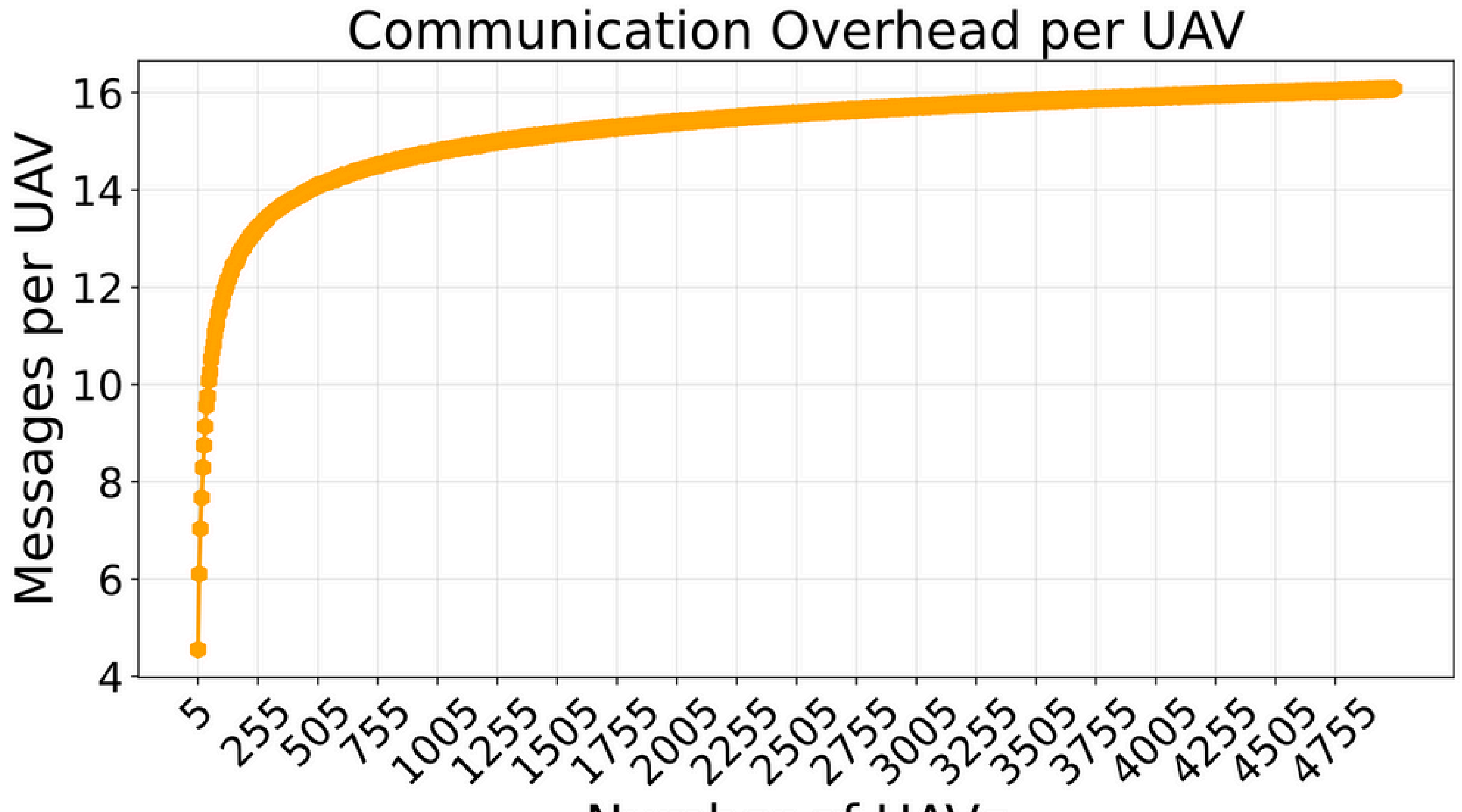
- Implemented in Python, program parallelized with Joblib to run on LIP6 cluster.
- Swarm sizes: 25-5000 UAVs, each 1000 runs
- Idealized conditions: no message loss nor obstacles.
- Metrics used: leader ratio, coverage rate, leadership quality, correctness and message overhead

Machine	Modèle	Mémoire	Processeurs	Cœurs	Disques	Carte réseau
small[1-24]	DELL PowerEdge R410	64 Go	2 x Intel Xeon E5645	12 cœurs / 24 threads @ 2.40 GHz	SSD 128 Go + HDD 4To	Broadcom NetXtreme II
tall[1-20]	DELL PowerEdge R440	384 Go	2 x Intel Xeon Silver 4216	32 cœurs / 64 threads @ 2.10 GHz	SSD 480 Go + HDD 4To	Broadcom NetXtreme II

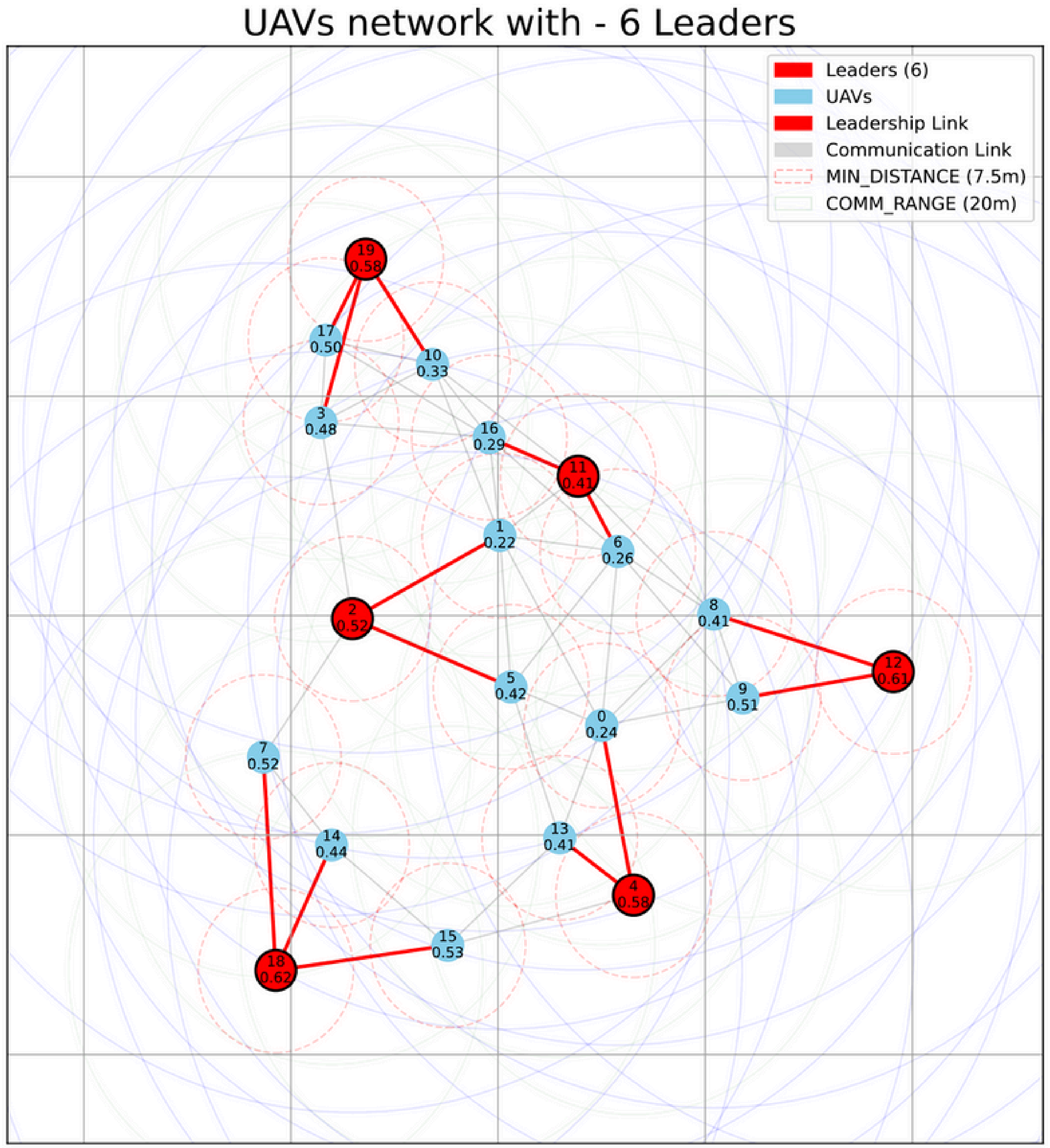
Results :

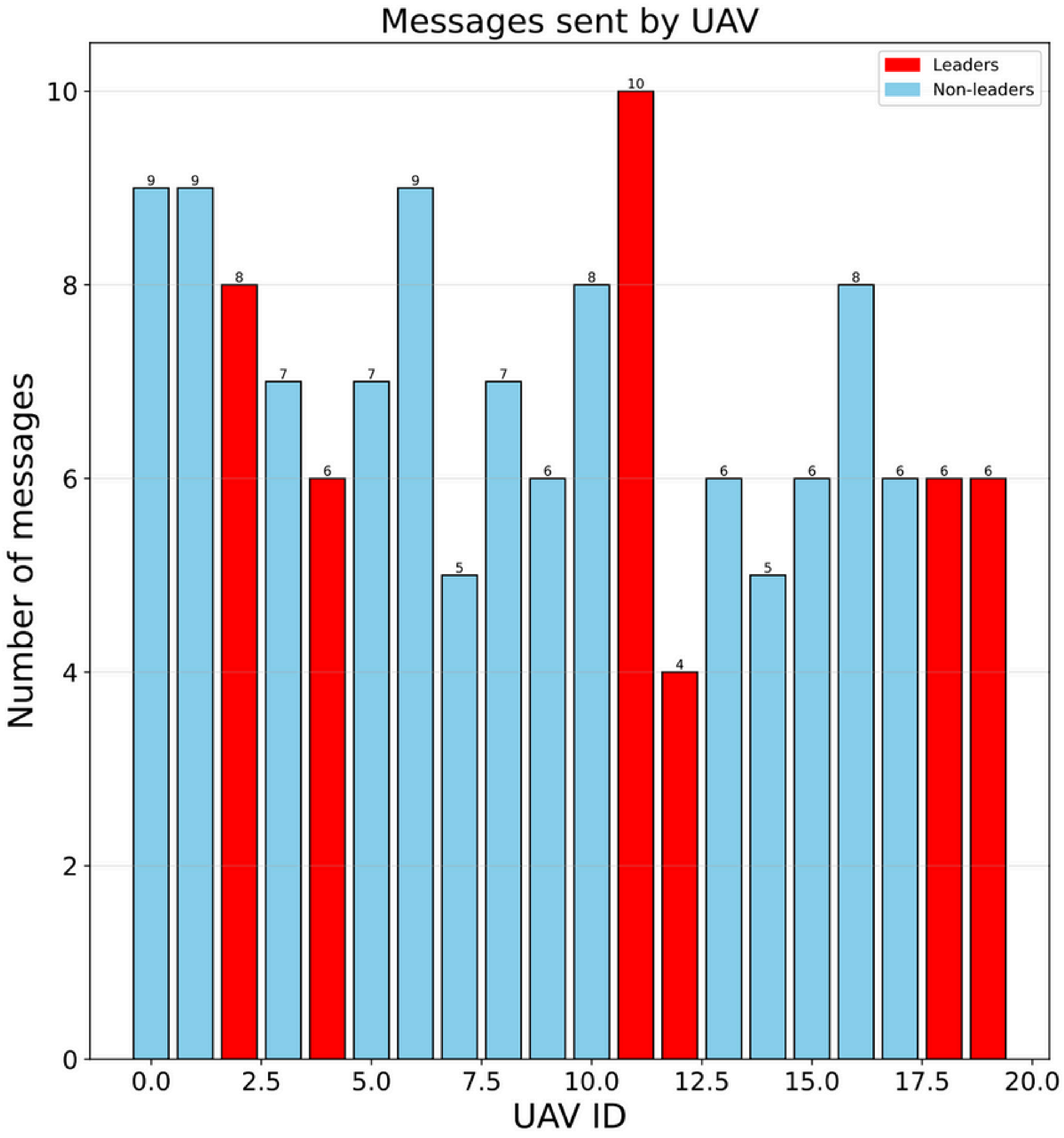
- Leadership ratio stabilizes between 0.15–0.20 regardless of swarm size.
- Coverage, quality and correctness all reach 100% **only through simulations.**
- Communication overhead grows linearly at network scale, sub-linearly per UAV.





Example : 20 UAVs Single simulation





- 6 Leaders based on the score
- Number of messages relatively low
- No errors of role assignement.

Future Work & Conclusion

Idealized Assumptions:

- Current model assumes ideal LoS.
- No environmental effects on communication
- Static UAV network
- Perfect sensors and no loss due to distance

Future work:

- Include message loss, environmental effects.
- Include 3D simulations with movement and all of the framework steps.
- Physical OWC implementation.

Thank you !