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Drone Fleet Coordination: How Self-Organisation Solves All Your Problems

Yann Busnel

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Submitted on 2 Jan 2023

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IMT Atlantique

Bretagne-Pays de la Loire
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DRONE FLEET COORDINATION

*HOW SELF-ORGANISATION
SOLVES ALL YOUR PROBLEMS*

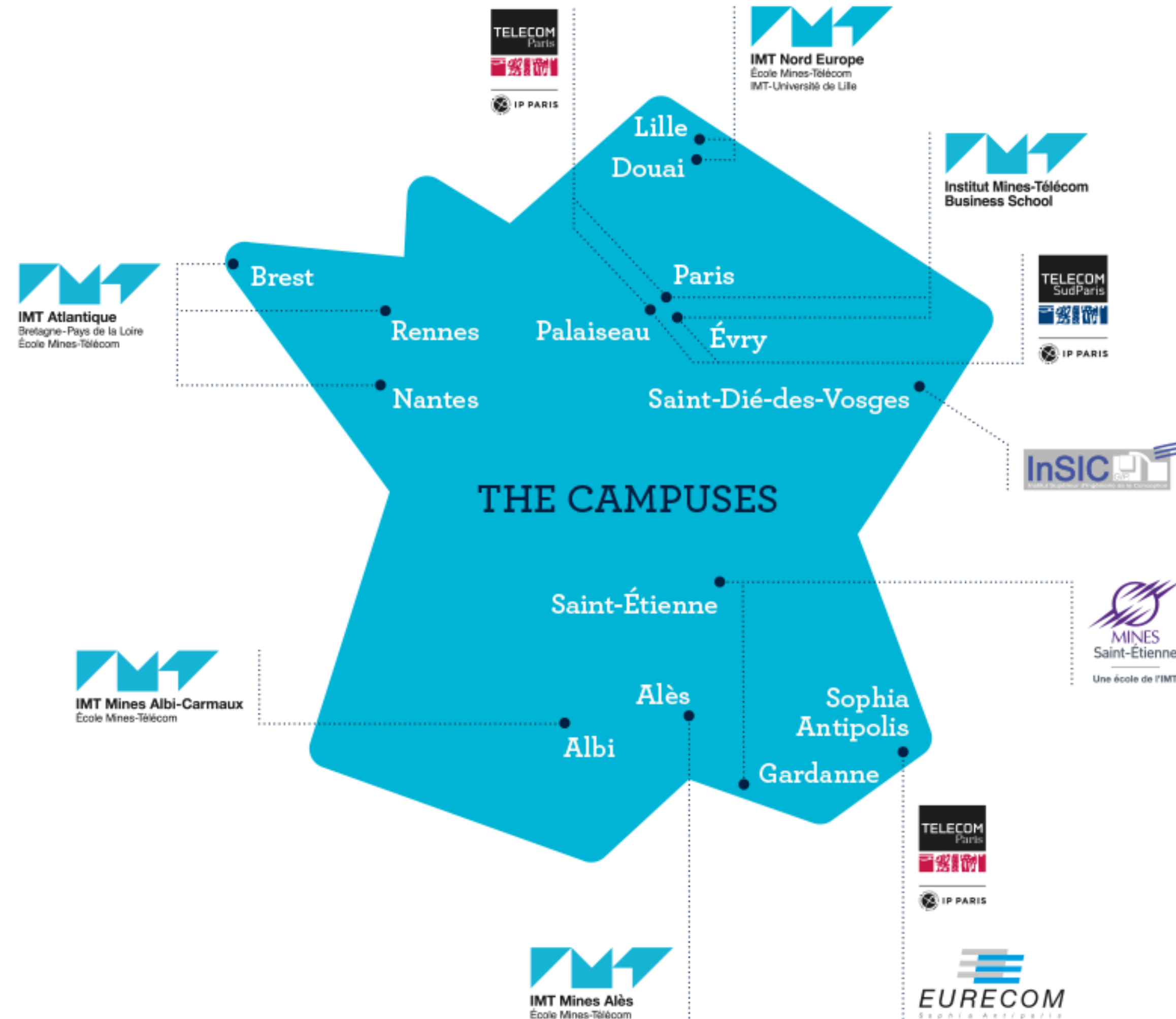
YANN BUSNEL

*JOINT WORKS WITH
CHRISTELLE CAILLOUET (UCA), DAVID COUDERT (INRIA),
IGOR DIAS DA SILVA (UCA)*

RESCOM SUMMER SCHOOL — GDR RSD — 28/06/22



WHAT IS IMT?



TEACHING

13,360
students

including

10,290 engineering/managers students
including **2,580** apprentices

1,190 management students
including **200** apprentices

1,220 PhD students

29% of whom are foreign students

34% of whom are scholarship students

4,460
degrees awarded

320,000
new enrollments / 44 sessions
active on 3 platforms with an
international audience
(Coursera, edX, fun-mooc)

9
new courses launched

15
projects in progress



MOOC

RESEARCH & INNOVATION

€ 75 millions

contractual resources from research,
development and innovation

2 Carnot Institutes:

M.I.N.E.S et Télécom & Société Numérique

1,958
articles in international journals

63
teaching and
research chairs

58
patent applications
in 2021

ENTREPRENEURSHIP & BUSINESS RELATIONS

79
enterprises created and 125 in stock in the incubators

500
jobs created

€ 100 M
raised

6,925
corporate partnerships
(SMEs and midcaps)



INSTITUTION

4,450
staff members
including **2,850**
professor-researchers, professors
and research engineers + doctoral and
post-doc students excluding CIFRE scheme

8
graduate schools
2
subsidiaries

1
foundation

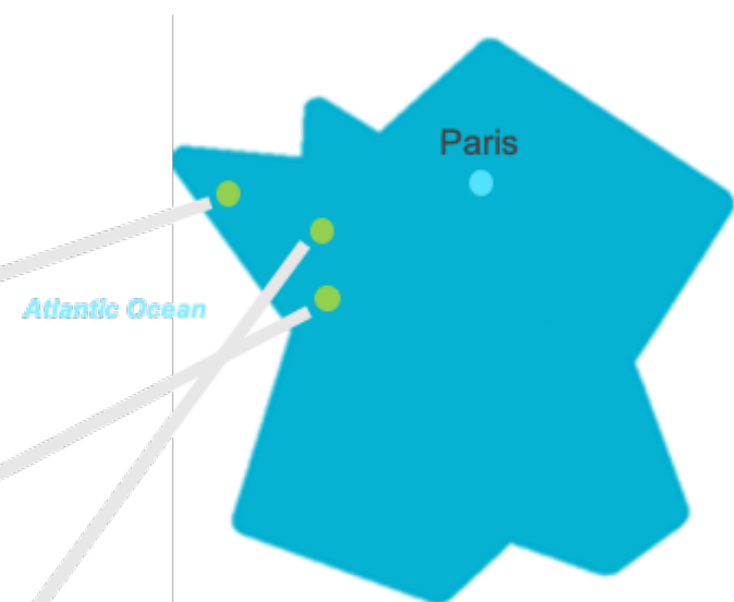


#Digital technology

#Energy

#Environment

3 CAMPUSES



Brest



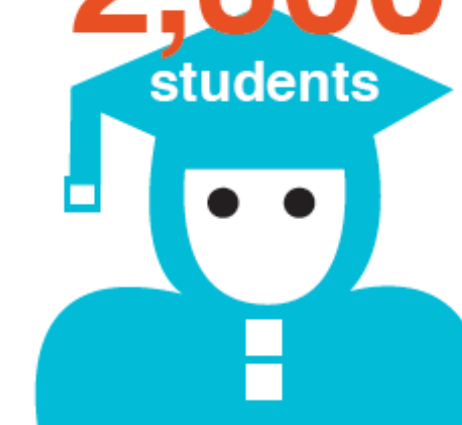
Nantes



Rennes

2,300

students



including 1,400 engineering students and 300 doctoral students



730

graduates / year

from MSc to PhD

780

staff



Including 500 permanent staff



290

permanent researchers

and research lecturers

on our campuses, including 110 HDRs (Researchers with supervisory accreditation)

+ 40% international students

+70 nationalities

€70

M budget

Including € 27 million of our resources, € 18 million of which from research contracts

International academic ranking



2022

Among the top 400 universities in the world

[Ranking detail](#)



2021

Ranked on 2 themes

[Ranking detail](#)



2022

Ranked on 5 subjects

[Ranking detail](#)

National academic ranking



2022

Classified in 5th position

[Ranking detail](#)



2022

Classified in 12th position

[Ranking detail](#)



2022

Classified in 10th position

[Ranking detail](#)



2022

1266th worldwide and 49th in France

[Ranking detail](#)



2022

7th in France with 40 indicators

[Ranking detail](#)



2022

Ranked 124th in the world

[Ranking detail](#)



2021

14th highest-ranked engineering university

[Ranking detail](#)



2021

1468th worldwide and 62nd in France

[Ranking detail](#)

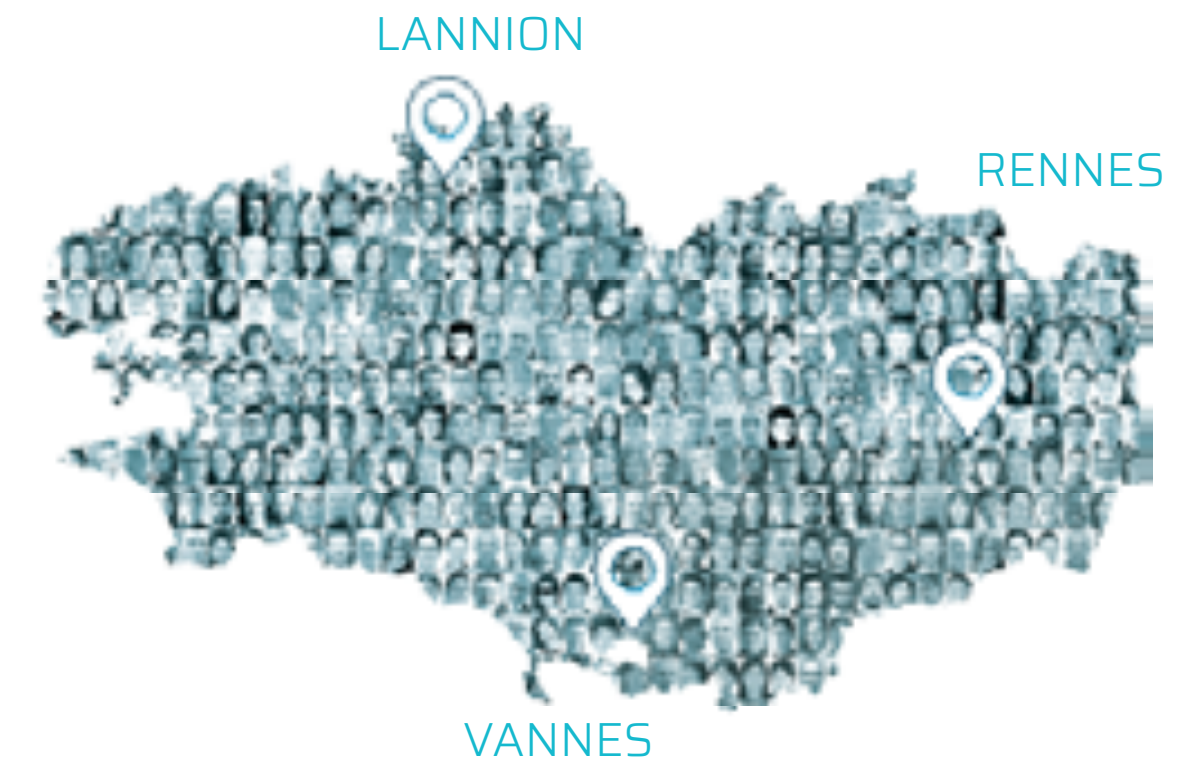
WHAT IS IRISA?



The french laboratory for
research and innovation in
digital science and technology



850
women and
men collaborators



700+
scientists

3
sites in
Brittany

40±
Research teams

1000+
publications
/year



A BIT OF HISTORY



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- **July 1849**
- **Austrians launched around two hundred pilotless balloons against the city of Venice**
 - Each carrying a 24- to 30-pound bomb
 - Austrians used smaller pilot balloons to determine the correct fuse settings



Time period

Institution

Iconic Drone

Usage

Phase 1
Target drone

Phase 2
Flying bomb drone

Phase 3
Surveillance

Phase 4
Hunter-Killer

Phase 5
Police drone

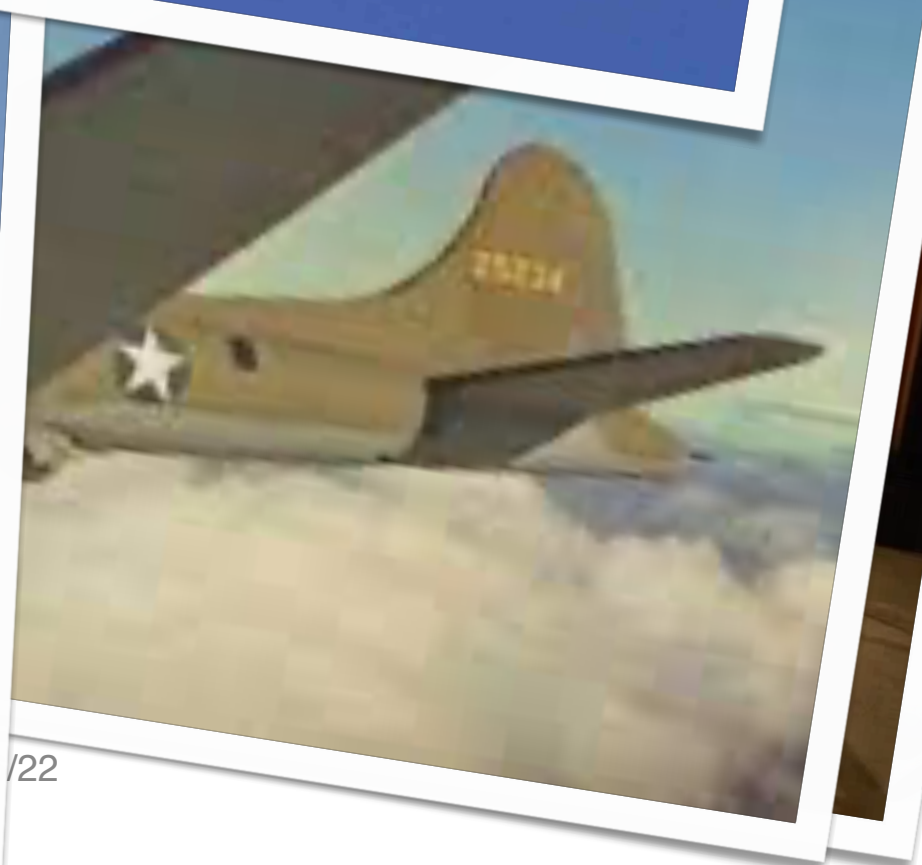
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ordinance
enemy lines

monied or
areas

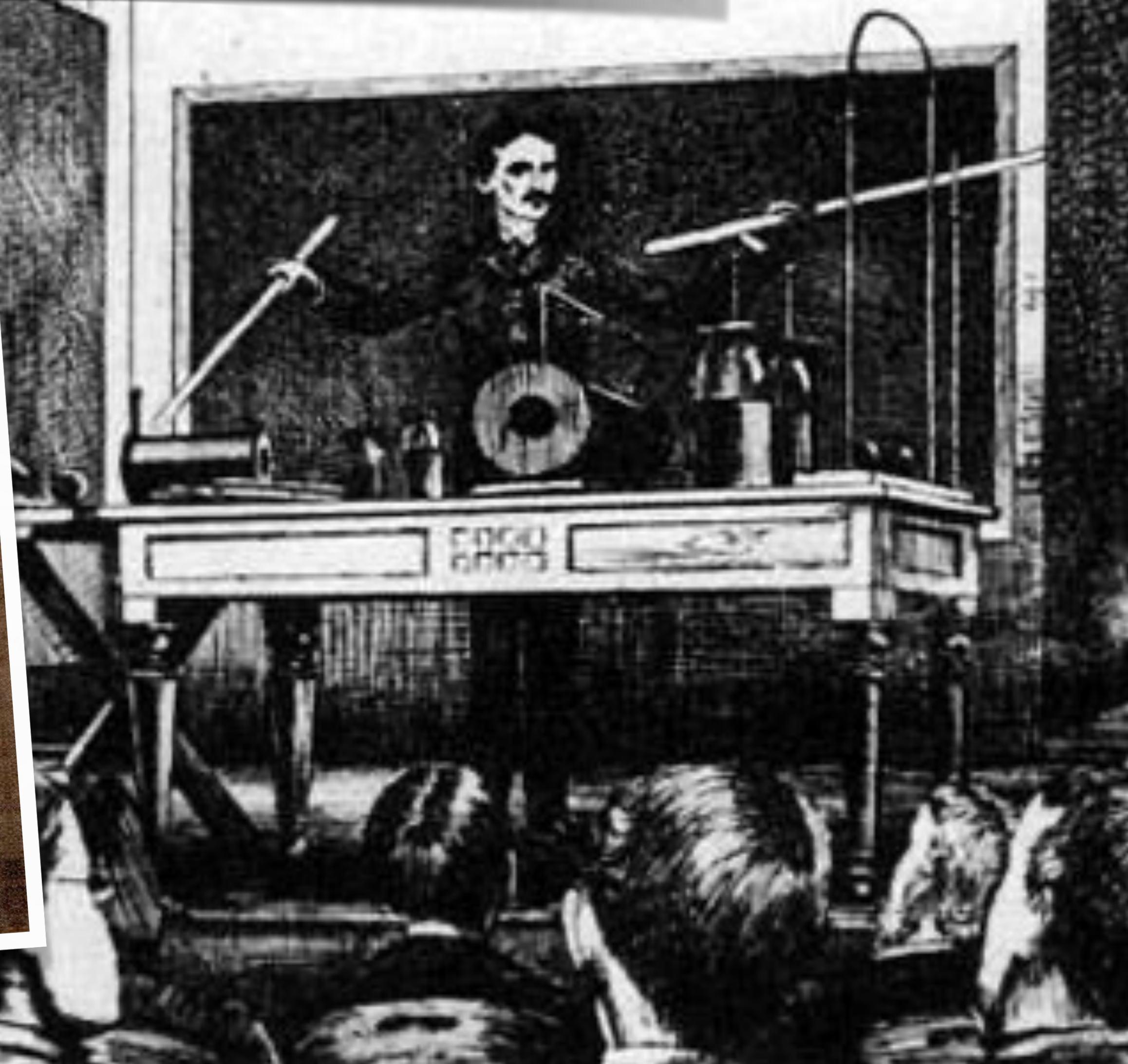
« hunt »
of terror

border
ance



IT'S ALL ABOUT THE RADIO...

Europe and America are united by telegraphic communication. Glory to God in the highest, on earth peace, goodwill to men.



FLIGHT-PLAN

1. A BRIEF OVERVIEW

- ⚡ Ideas and open issues in distributed fleet of drones

2. DISASTER MANAGEMENT

- ⚡ Automatic guarantee for coverage and connectivity

3. EXTENDING THE LIFESPAN OF AN IOT NETWORK

- ⚡ Optimize RF harvesting

AUTONOMOUS FLEET OF DRONES A BRIEF OVERVIEW



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Unmanned Aerial Vehicles (UAVs)

- Autonomous flying devices providing services to targets on the ground
- Air-to-ground and air-to-air communications
- Light materials with low energy consumption machines

➤ Advantages

- Solution to anytime and anywhere network access
- Reduce costs of network management
- Outperform the impossibility of ground access and communications
- Bring an additional dimension to the network

➤ Applications

- Collaboration among mobile devices for a specific task :
- Disaster management systems
- Monitoring and tracking
- Health related applications
- ...

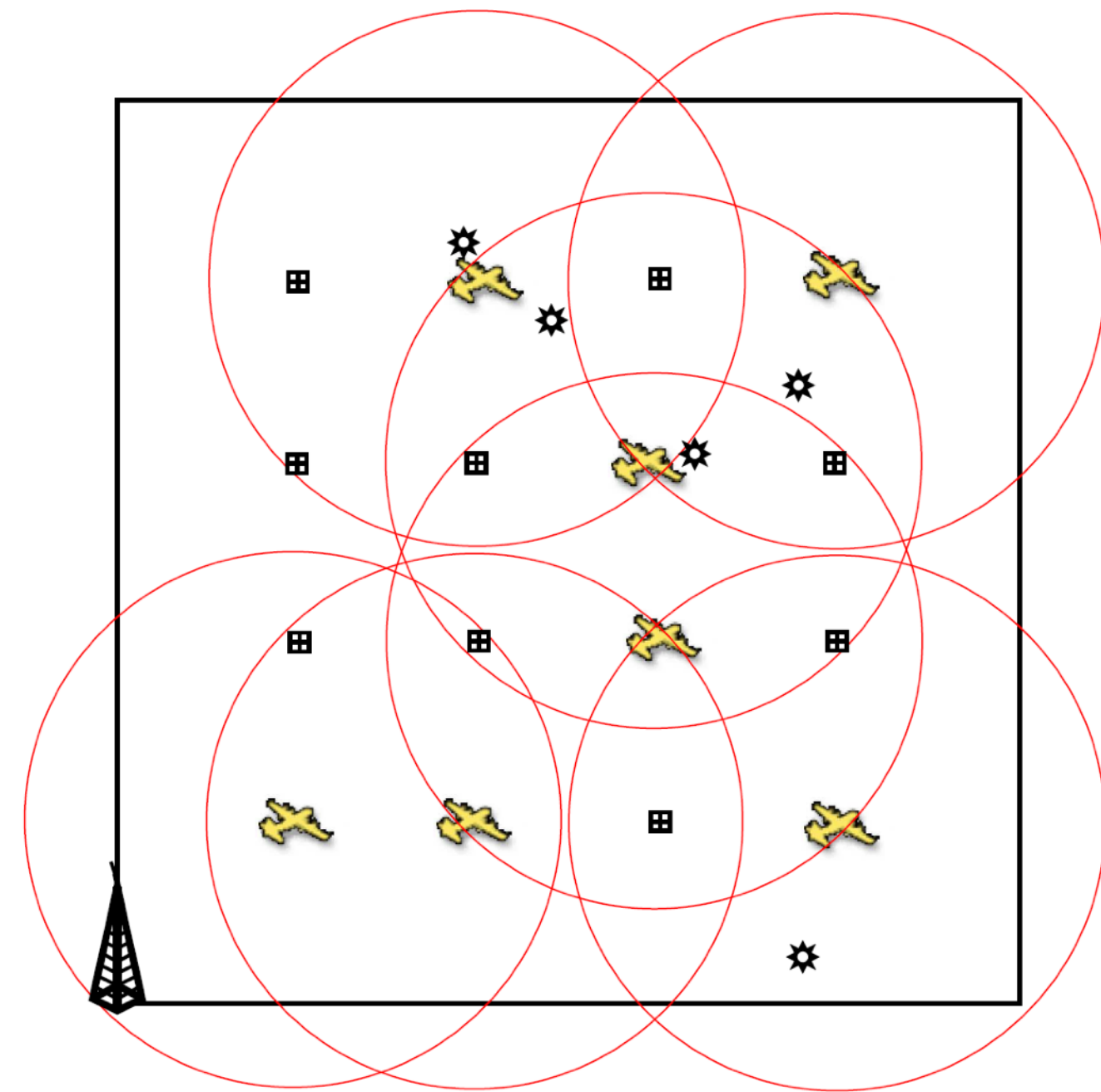


OBJECTIVES



Yann Busnel, Christelle Caillouet, David Coudert.
Self-organized UAV-based Supervision and Connectivity: Challenges and Opportunities.
18th IEEE International Symposium on Network Computing and
Applications (NCA 2019), Cambridge, United States, September 2019

WHICH TOOLS AND TECHNIQUES COULD BE CANDIDATES FOR AUTOMATIC ANALYSIS AND OPTIMIZATION OF THE COMPLEXITY OF COMMUNICATION ?



→ **Deployment of connected UAVs to cover targets and provide network services**

➤ **Assumptions and goals :**

- Fixed (or mobile) unknown target positions
- Connected set of UAVs with a base station
- Air-to-ground + air-to-air communications
- Quality of service
- Costs
- Scalability

➤ Centralized optimization

- Optimal deployment
- Cost minimization
 - Energy
 - Number of drones needed for connectivity
 - Altitude

➤ Distributed algorithm

- Target localization
- The drones
 - Autonomously discover the ground users
 - Continuously connected with the base station



➤ Distributed algorithms

- Probabilistic protocols (*e.g.* epidemic) based on periodic exchanges of information between participants
- Algorithms for wired networks based on high communication paradigms

➤ Large-scale systems design

- Overlay networks usually for one specific application
- Group nodes depending on computational power
- Algorithms based on centralized information gathering

➤ No direct good candidates for drone fleet applications



1. Real time applications

- Centralized solutions not applicable
- Low latency and battery consumption

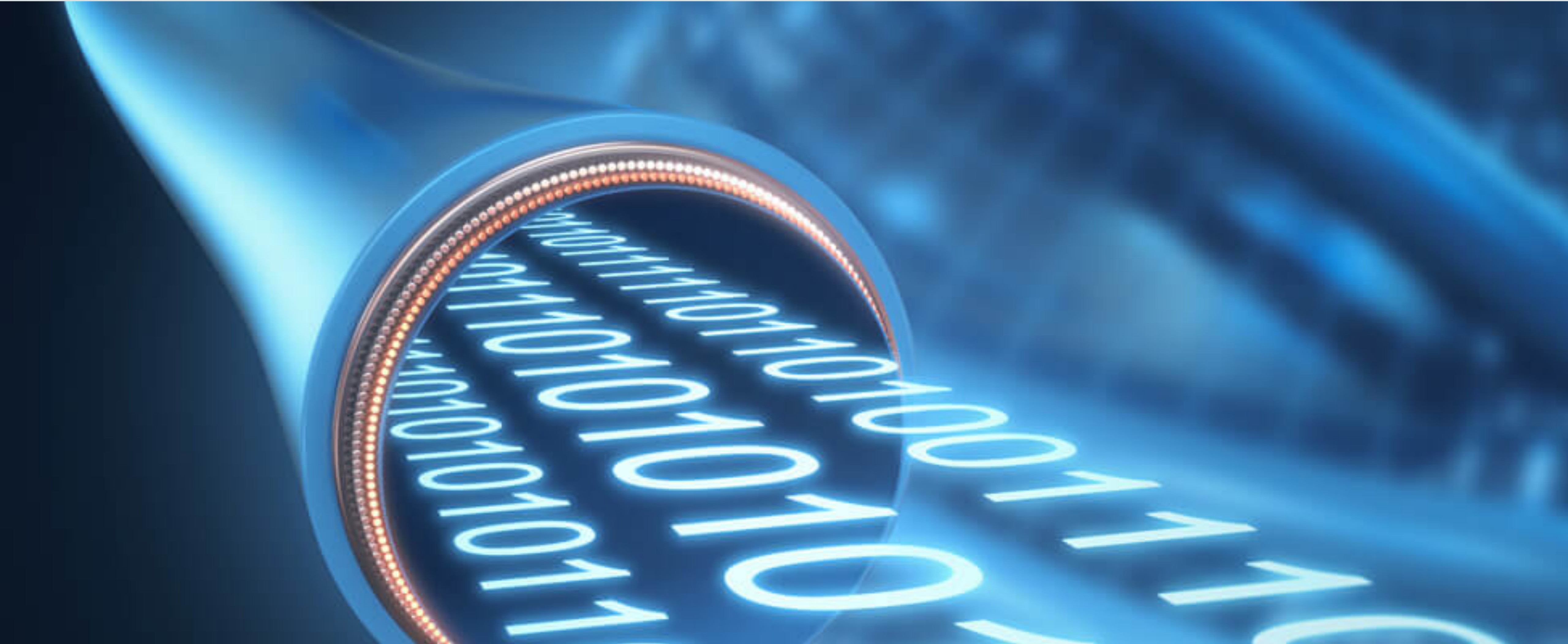
2. Large scale deployment

- Centralized information gathering and manual allocation of resources do not scale
- Track the distribution of available resources

3. Low storage and processing capacities

- Important amount of data to process quickly and accurately
- Diversity and dynamic nature of content





➤ **Extract relevant information**

- Equivalent to anomaly detection
- Existing algorithms based on complete knowledge or high computational cost

New approaches for real-time processing of massive (distributed) data flows

➤ **Data streaming methods**

- Sketch and sampling
- End-point computing optimization

Analyze the data stream and retain only relevant information to reduce memory

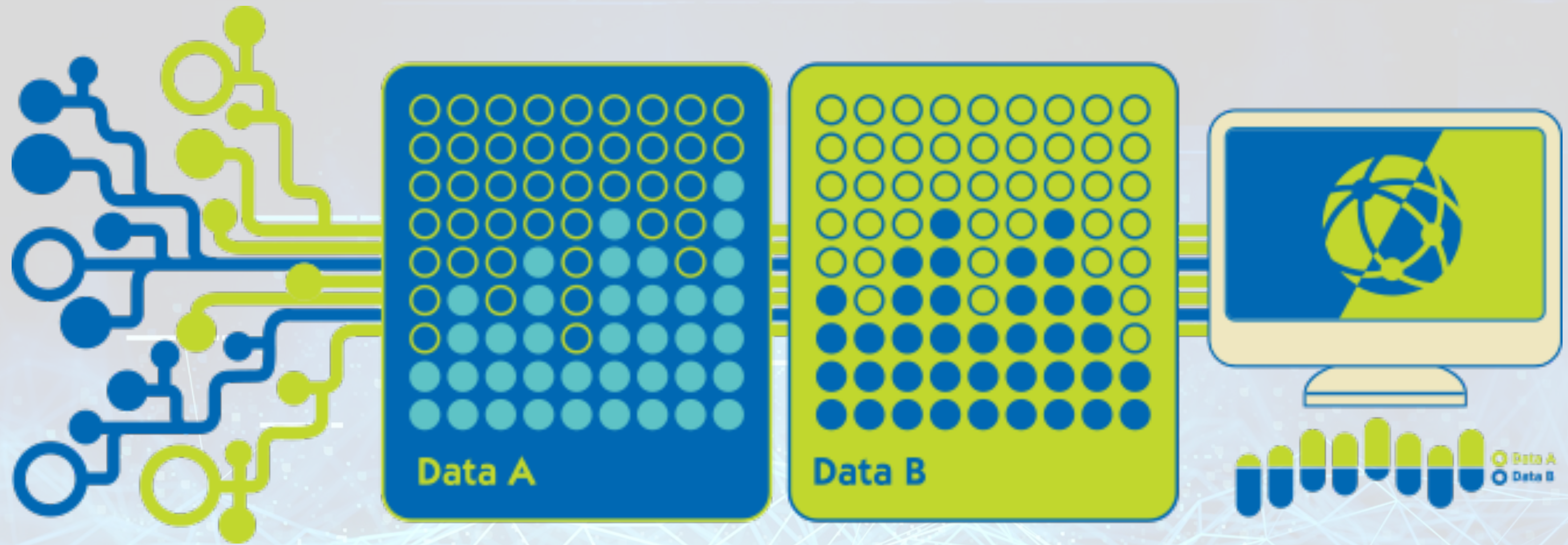


➤ Sketching techniques

- Process **all the data** in the stream on the fly, and to keep only summaries
- **Extracts statistics** on processed data streams, with bounded error probabilities
- Based on **summaries** that involve a significant loss of information, with sometimes drastic overestimation

➤ Interesting techniques

- Using **Count-Min Sketch** for complete information
- **Histogram aggregates** for sliding windows



- **Frequency estimation of any item**

 - (ϵ, δ) -additive-approximation of m_i

- **One vector C of size $k = \lceil e/\epsilon \rceil$**

- **One 2-universal hash function h**

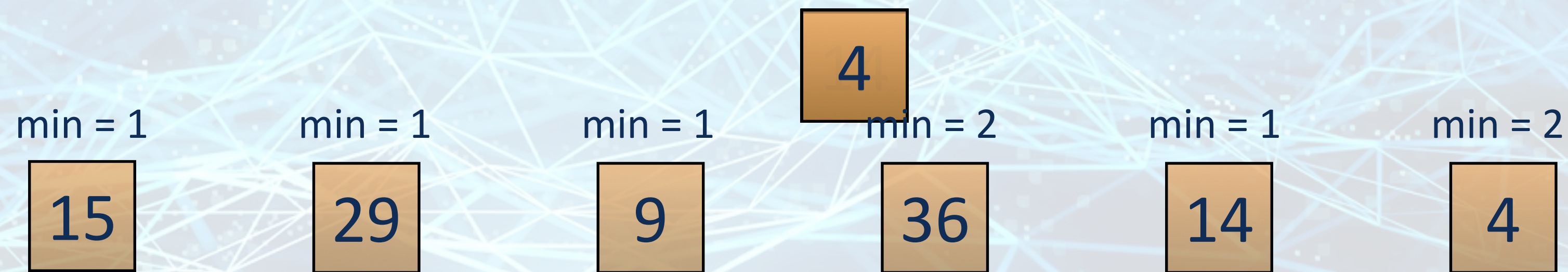
- **For each item v**

 - $C[h(v)] ++$

COMPUTE $\lceil \log 1/\delta \rceil$ ESTIMATORS IN PARALLEL
AND RETURN THE MINIMUM VALUE

4 14 36 9 29 4 36 15

$h_1(.)$					$h_1(15)=1$
$h_2(.)$					$h_2(15)=3$
$h_3(.)$					$h_3(15)=2$



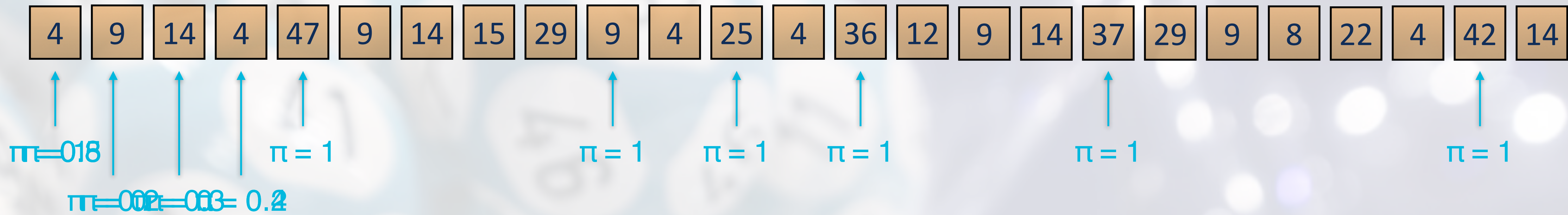


➤ Sampling in real-time data

- Limit the **amount of data stored** in memory
- **Computing** exactly functions on these samples
- Depends strongly on the **volume** of data sampled, and their **position** on the stream

➤ Interesting techniques

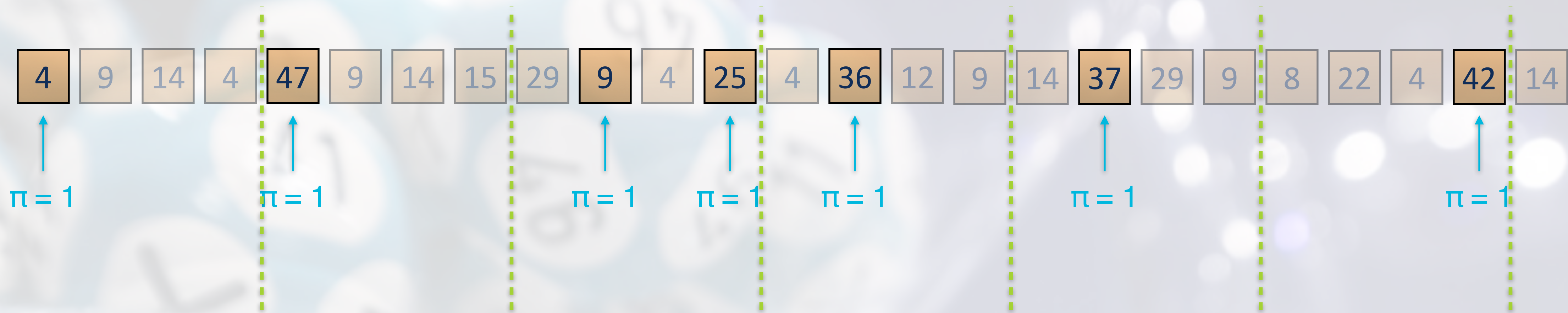
- Using **Bloom filter** for complete information
- **Pivotal** (or Cube) **Sampling** for sliding windows



$$(\tilde{\pi}_i, \tilde{\pi}_j) = \begin{cases} (\min(1, \pi_i + \pi_j), \max(\pi_i + \pi_j - 1, 0)) \\ \quad \text{with probability } q \\ (\min(\pi_i + \pi_j, 1), \max(0, \pi_i + \pi_j - 1)) \\ \quad \text{with probability } 1 - q, \end{cases}$$

with

$$q = \frac{\min(1, \pi_i + \pi_j) - \pi_j}{2 \min(1, \pi_i + \pi_j) - \pi_i - \pi_j}$$



➤ Guaranteed properties

- Stable number of sample among a window
- Difficult to predict the selection in advance
- Fine stratification : balanced spreading according to time

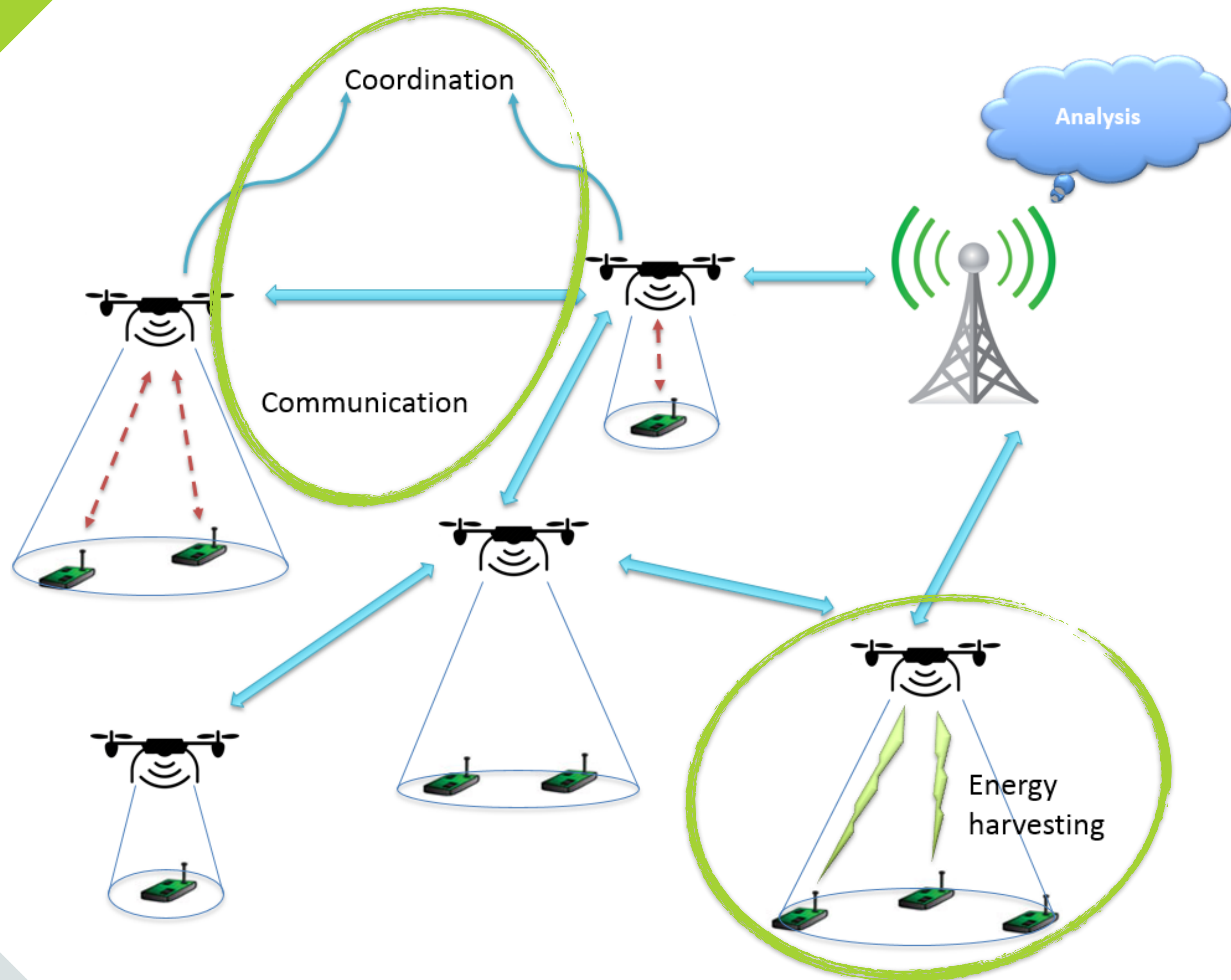
➤ Possible to generalize the pivotal sampling

- Contest of r items instead of 2 at each round : increase the unpredictability

- **Surpass, either in latency or battery consumption, two main approaches**
 - strictly local computation
 - delegation of data to the cloud services on the Internet
- **Innovative real-time solutions with low complexity**
 - in terms of memory, processing time, communication, etc.
- **Design a large-scale overlay network**
 - build and maintain application-level network
 - link together participating processes
 - communicate and inter-operate

- **Multi-topic openness involving cooperation between specialists from different fields**
- **Hot topic with various practical applications**
 - Security,
 - Disaster management
 - Energy
 - Agriculture
 - Traffic management
 - *etc.*

TUTORIAL'S NEXT STEPS



AUTONOMOUS FLEET OF DRONES FOR DISASTER MANAGEMENT



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Amatrice, Italia, 2016



Fukushima, Japan, 2009

Yann Busnel, Christelle Caillouet, David Coudert.
Self-organized Disaster Management System by Distributed Deployment of Connected UAVs.
In 6th IEEE International Conference on Information and Communication Technologies for
Disaster Management (ICT-DM 2019), Paris, France, December 2019

HOW TO DEPLOY IN REAL-TIME A FLEET OF DRONES TO GUARANTEE COVERAGE AND CONNECTIVITY?

CONSTRAINED TARGET COVERAGE PROBLEM

Given a **set of targets** located on the ground field, the goal is to monitor the area with flying drones to **cover as many targets as possible** and **ensure the connectivity** with a base station to continuously report or broadcast information to and from the sink

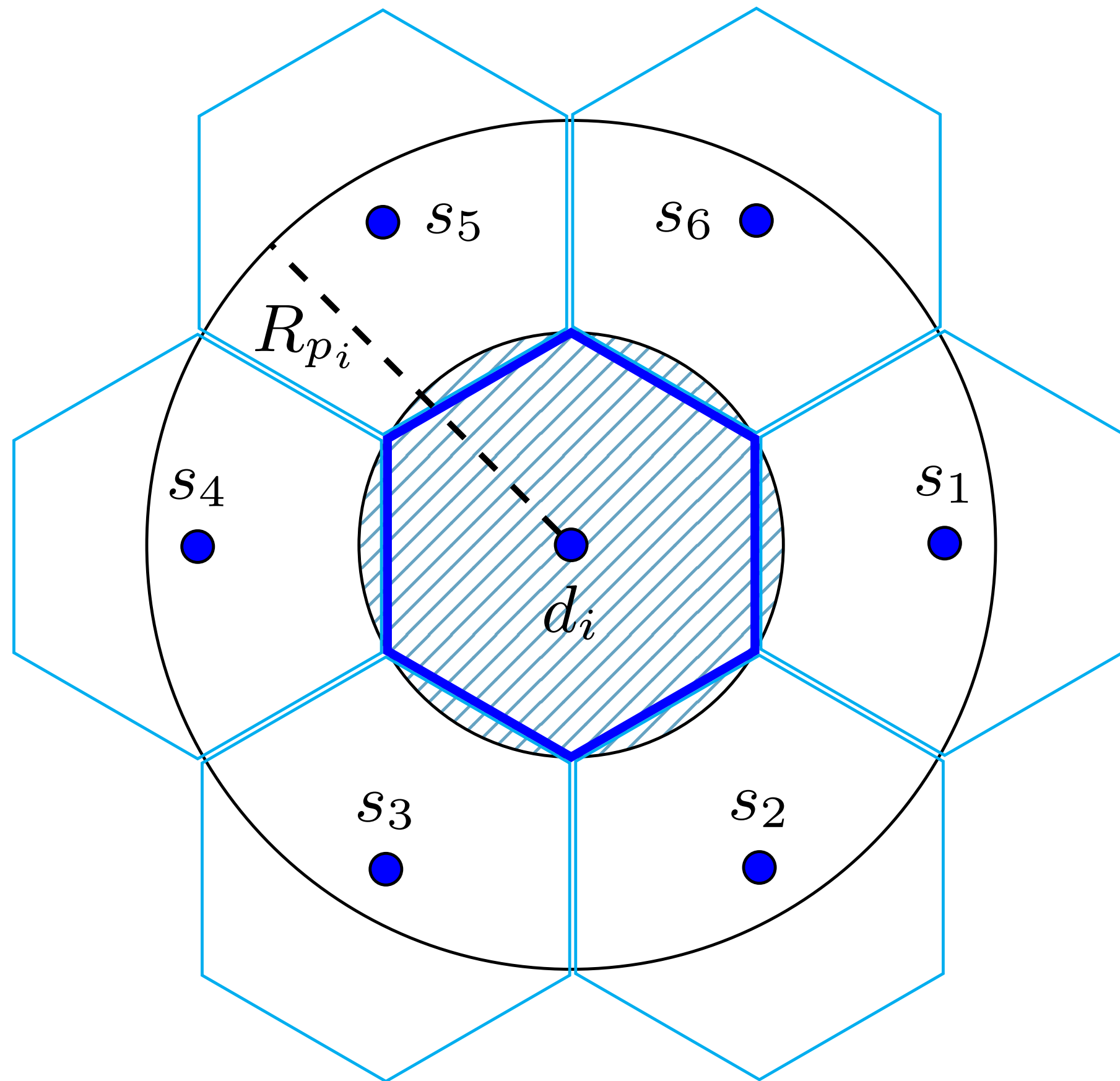


➤ *Vehicle Spreading using Self-organized Parallel Algorithm*

➤ **Extend existing works in the following way :**

- Unknown target locations
 - The drones must fly over the field and detect the targets while flying over.
- Distributed decentralized algorithm
 - Run by each drone using only information from their neighbors.
- Connectivity guarantee between the discovered targets and the sink
 - Drones form a multi-hop aerial wireless path
 - Once a target is detected, the drones self-organize to construct the path.
- Expansion iteration to use any available drones
 - Maximize the size of the observed area and the efficiency of the target detection

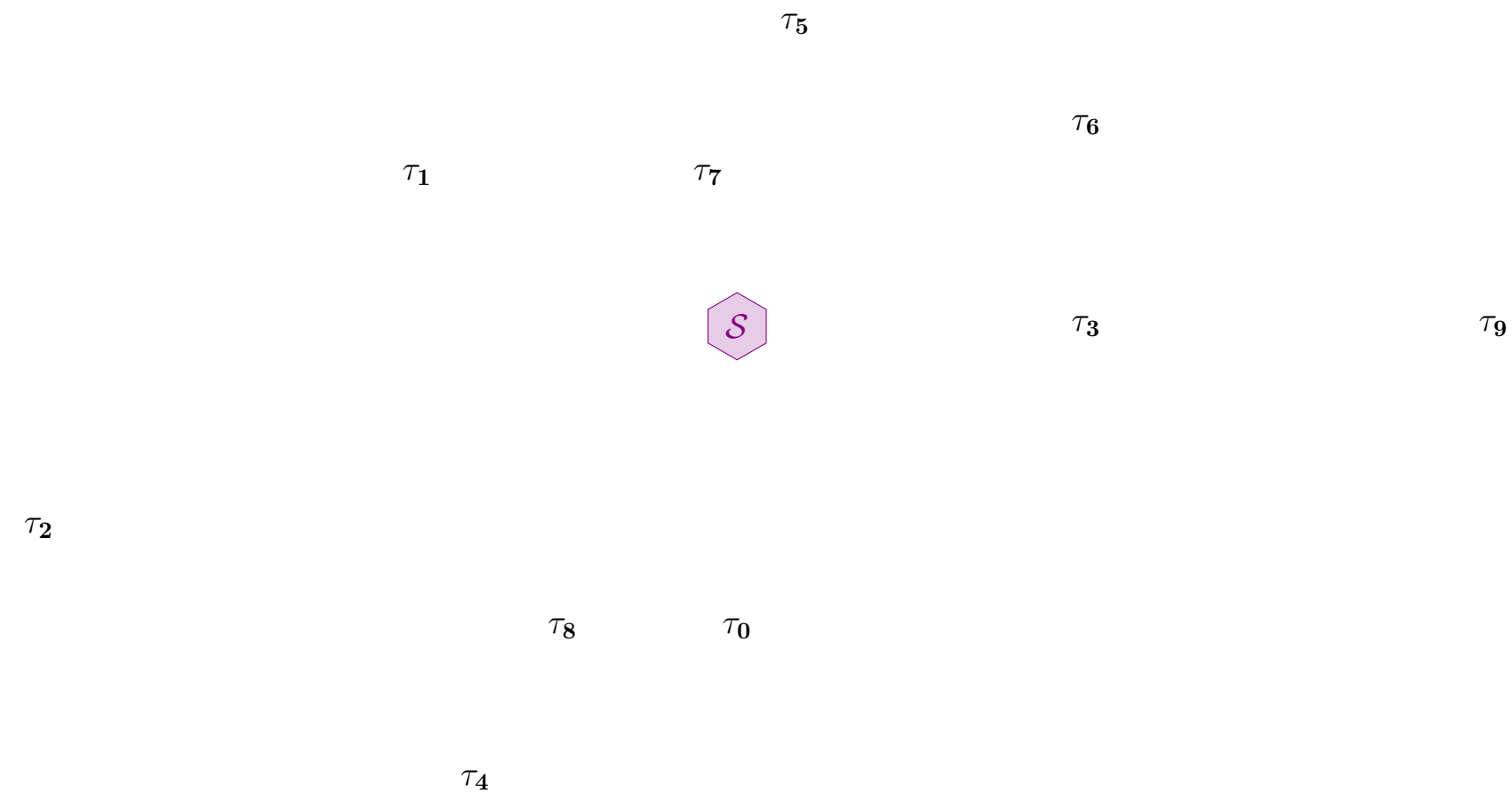




- Let D be a population of drones, identified by their id $d_i, i \in \{1, \dots, |D|\}$
- Let $p_i = (x_i, y_i, z_i)$ be the position of d_i
- The sink S is located at $p_s = (x_s, y_s, z_s)$
- Each drone d_i is equipped with an omnidirectional antenna. It is able to communicate with other drones or Pol located within a ball of radius R_{p_i}
- Let T be a set of target points, or Pol

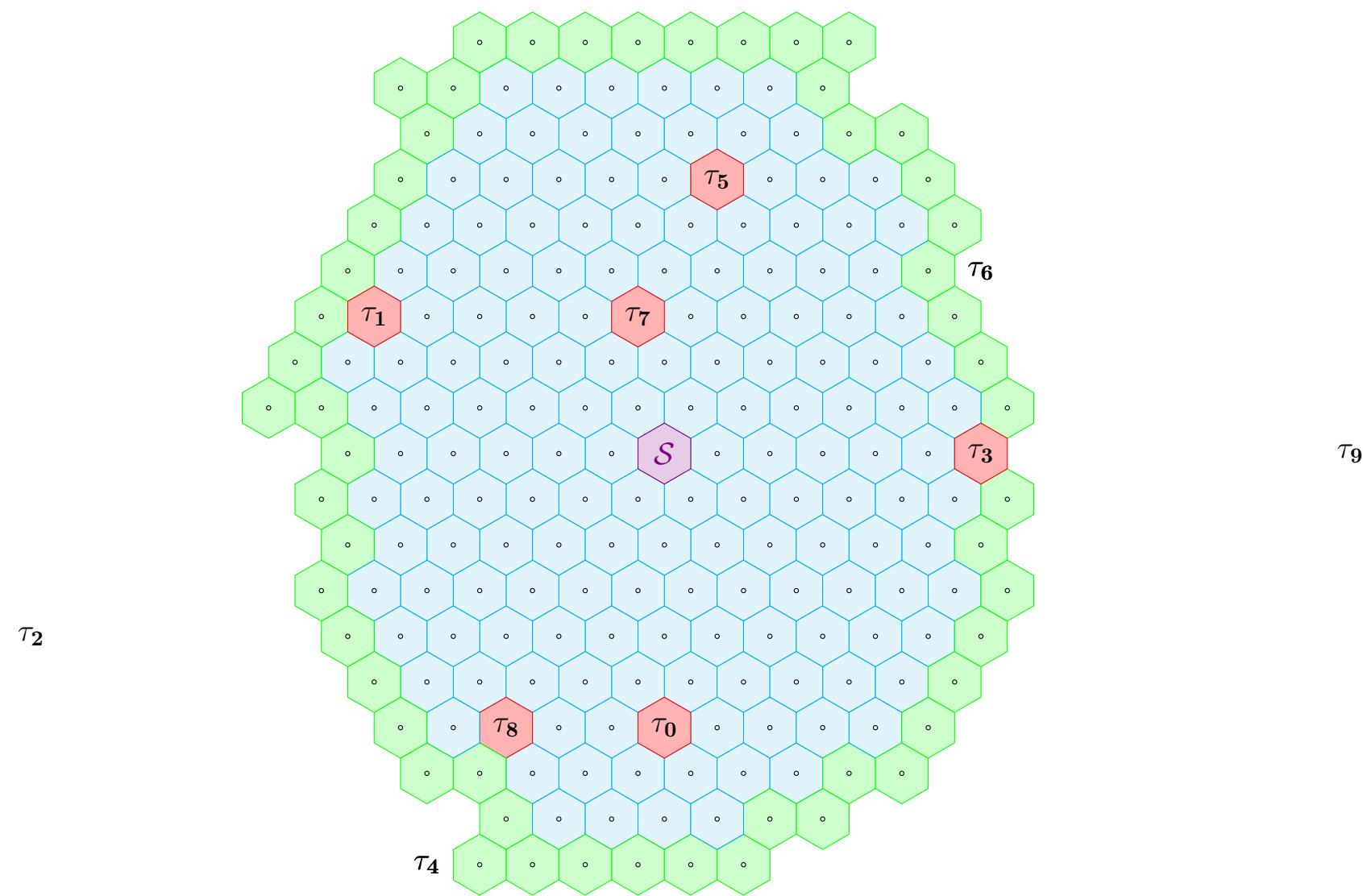
- All the n drones start at position p_s
- Each drone runs independently the algorithm following an alternating of 3 phases
 - Expansion phase
 - Spanning phase
 - Balancing phase
- Each drone can take 3 possible states
 - Irremovable
 - Border
 - Free



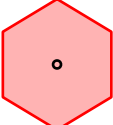
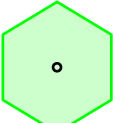
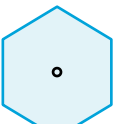


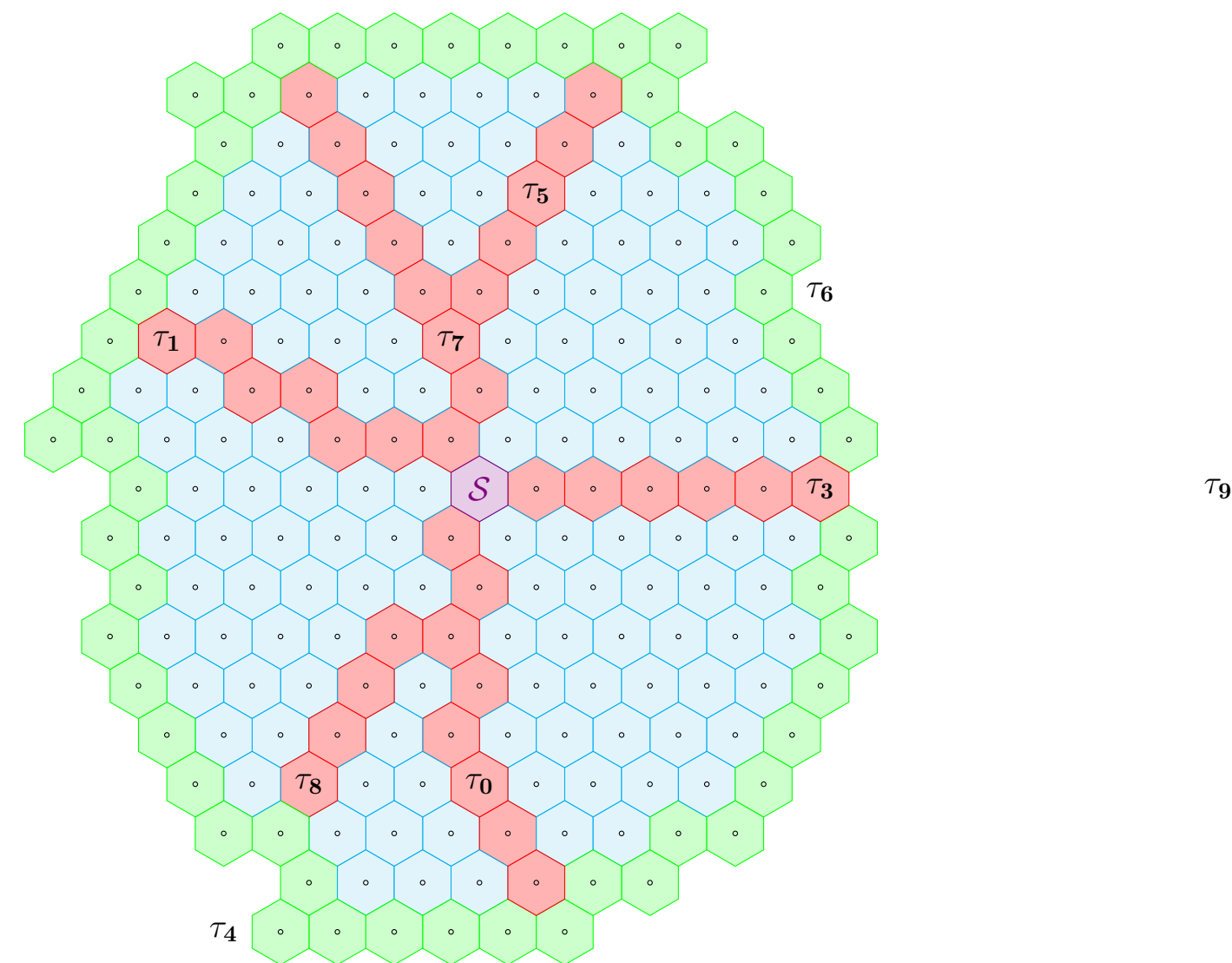
- **Round 0 - Initialization**
- **All drones are located at S**
- **10 targets to discover**

- Round 1 - End of Expansion phase
- All drones have spread around S
 - Connectivity is guaranteed



➤ Key

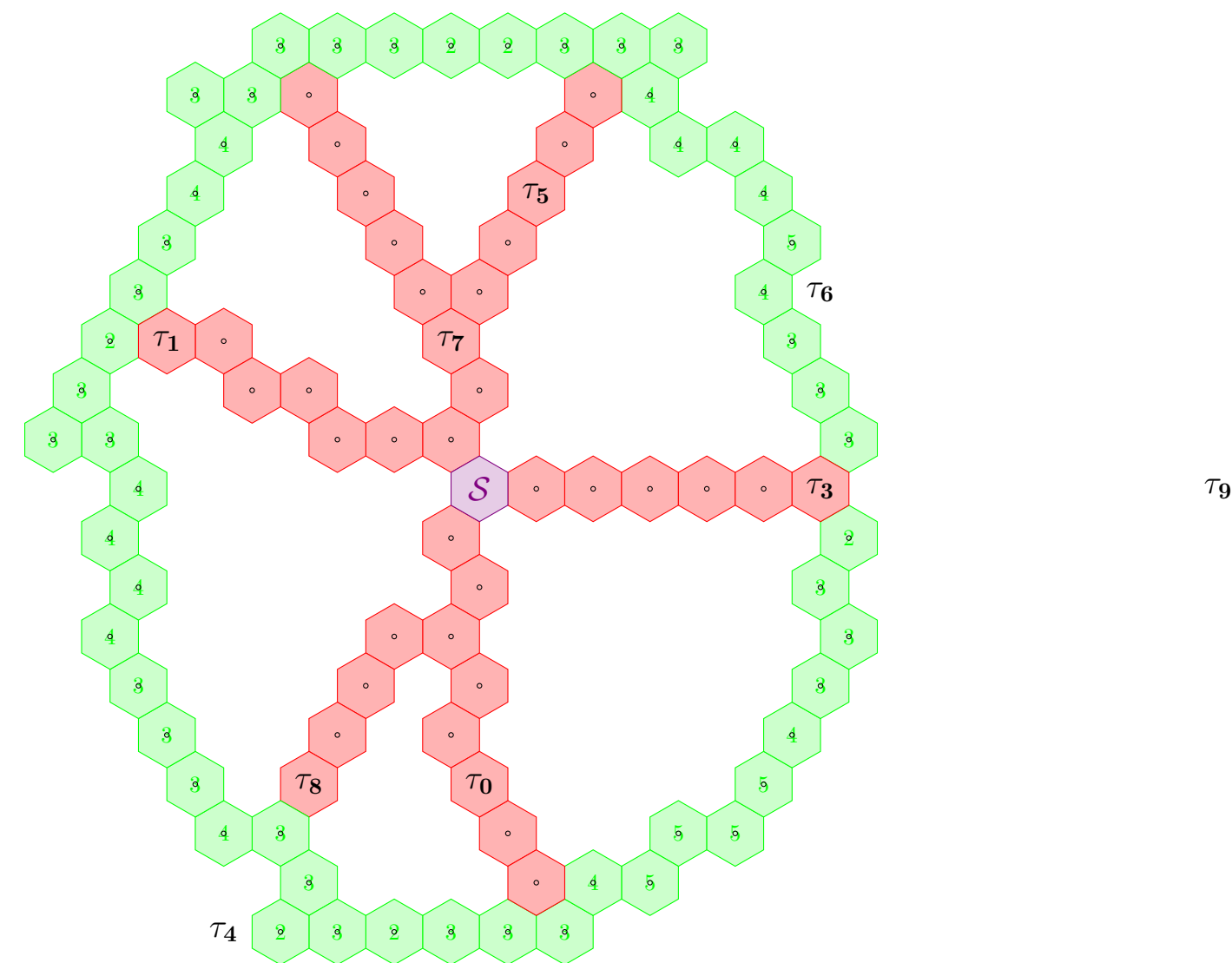
-  Irremovable
-  Border
-  Free



- **Round 1 - End of Spanning phase**
- **Drones have self-organized a spanning tree from the border to the sink S**
- **Connectivity is guaranteed**
 - From any point of the border
 - From any detected target

➤ Key

- ◻ Irremovable
- ◻ Border
- ◻ Free



➤ Round 1 - End of Balancing phase

➤ All free drones have moved to the border

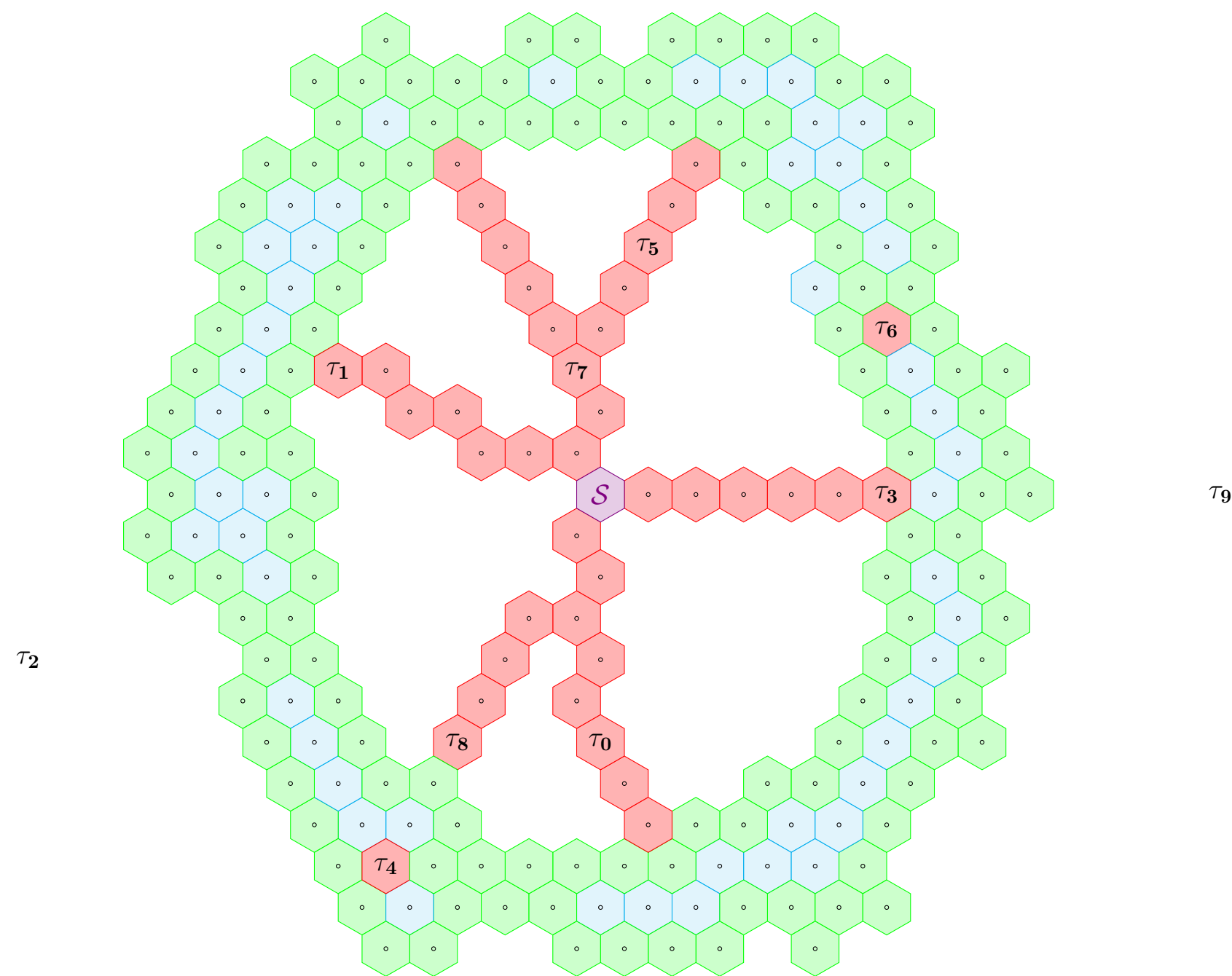
- Autonomous movement away from the sink
- Well-balanced all around the border

➤ Connectivity is guaranteed

- From any point of the border
 - and thus from any drone in the fleet

➤ Key

- ◻ Irremovable
- ◻ Border
- ◻ Free



➤ Round 2 - End of Expansion phase

➤ Any free drones have moved away from the former border

➤ A new border is self-defined by surrounding observation

➤ Connectivity is still guaranteed

➤ From any drone using the previous spanning tree

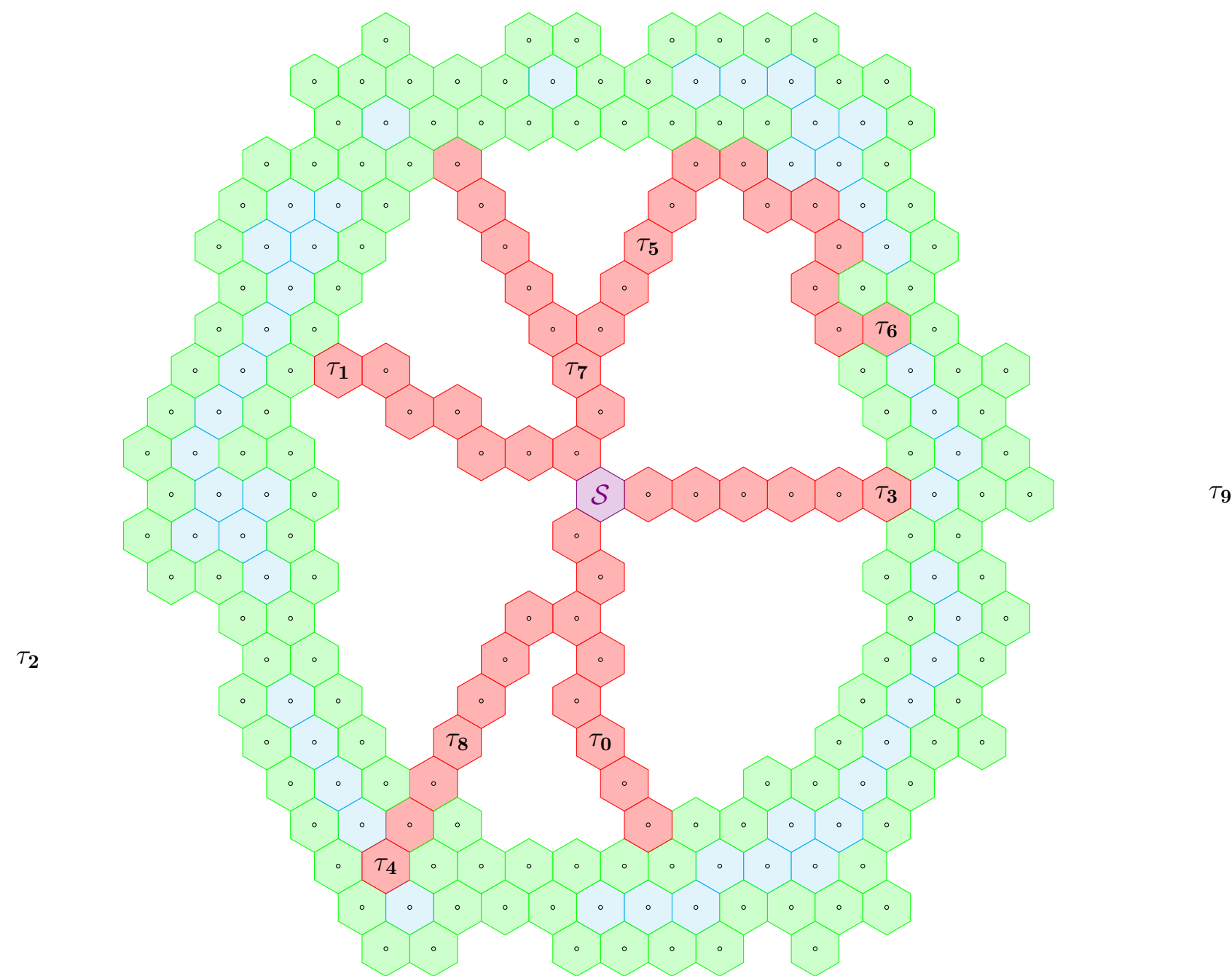
➤ Use of the right hand algorithm to find a path to the sink

➤ Key

 Irremovable

 Border

 Free



➤ Round 2 - During the Spanning phase

➤ Drones that discovered a new target extended the previous spanning tree

➤ Use of the right hand algorithm when progression is not possible (due to a hole on the coverage – cf. t_6)

➤ Connectivity is still guaranteed

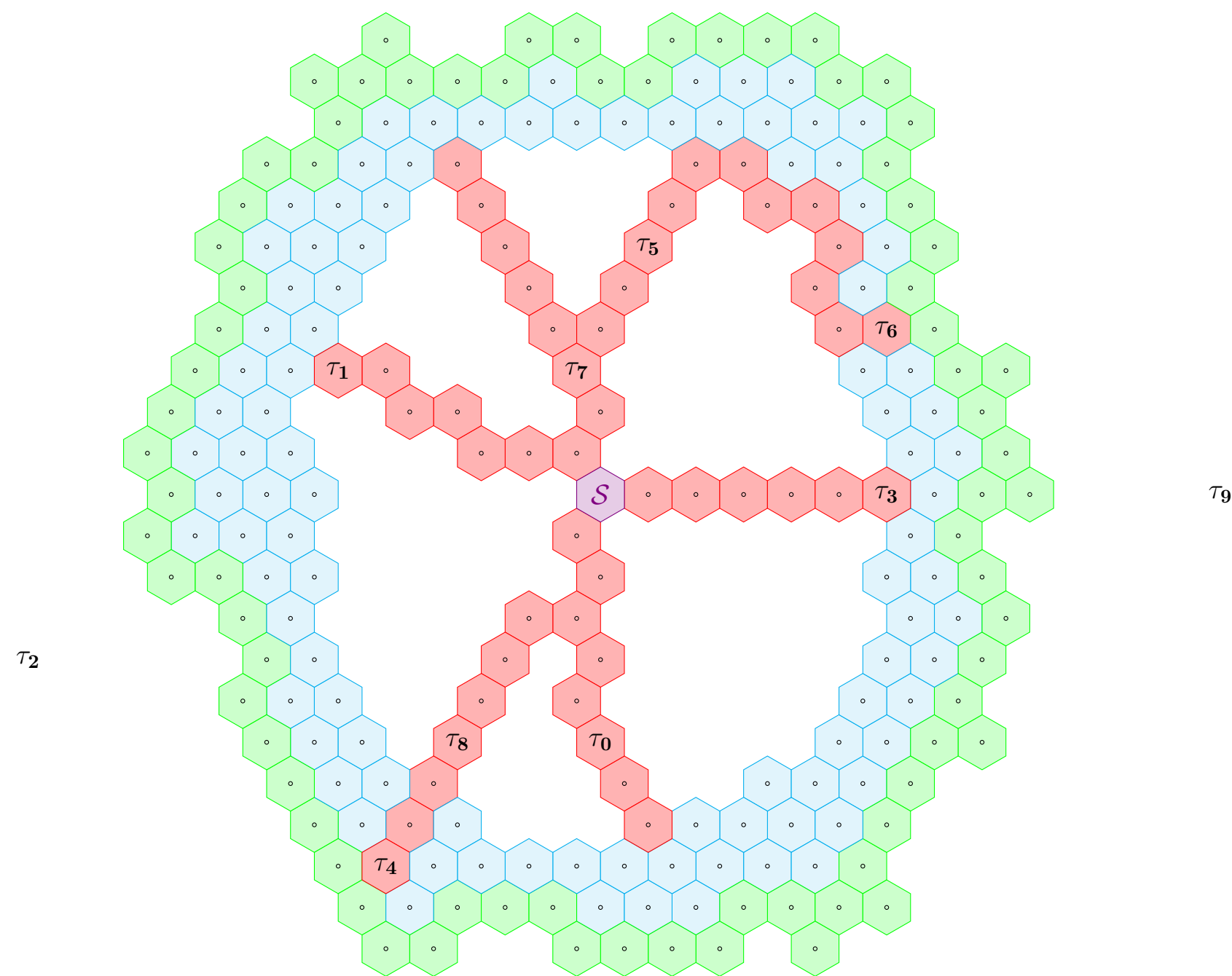
➤ By transitivity from the previous state

➤ Key

◻ Irremovable

◻ Border

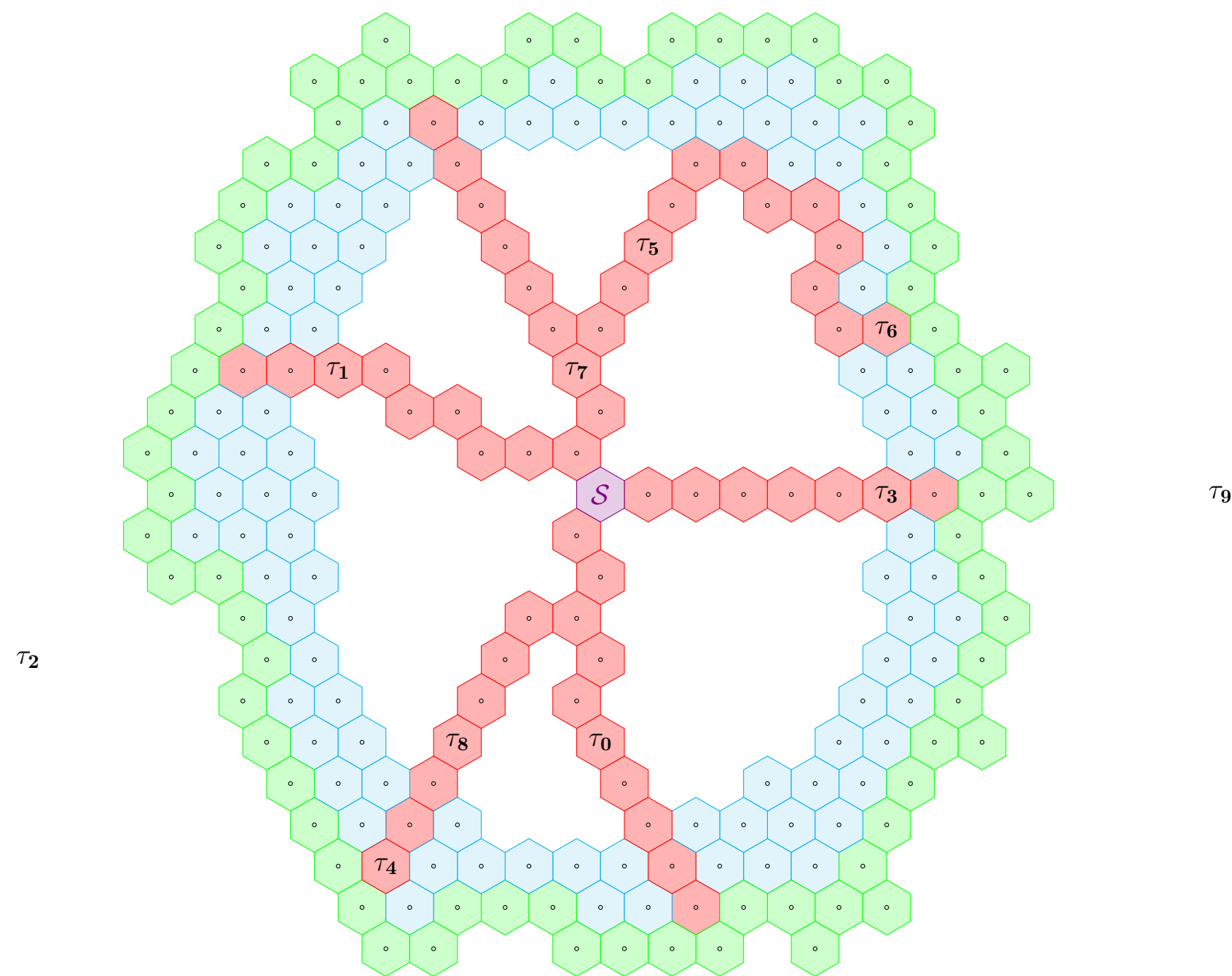
◻ Free



- **Round 2 - During the Spanning phase**
- **Any drone that is not irremovable, nor on the new external border became Free**
- **Connectivity is still guaranteed**
 - By transitivity from the previous state

➤ Key

- ◻ Irremovable
- ◻ Border
- ◻ Free



➤ **Round 2 - End of Spanning phase**

➤ **Border and Free drones extended the spanning tree to the external border**

➤ **Connectivity is still guaranteed**

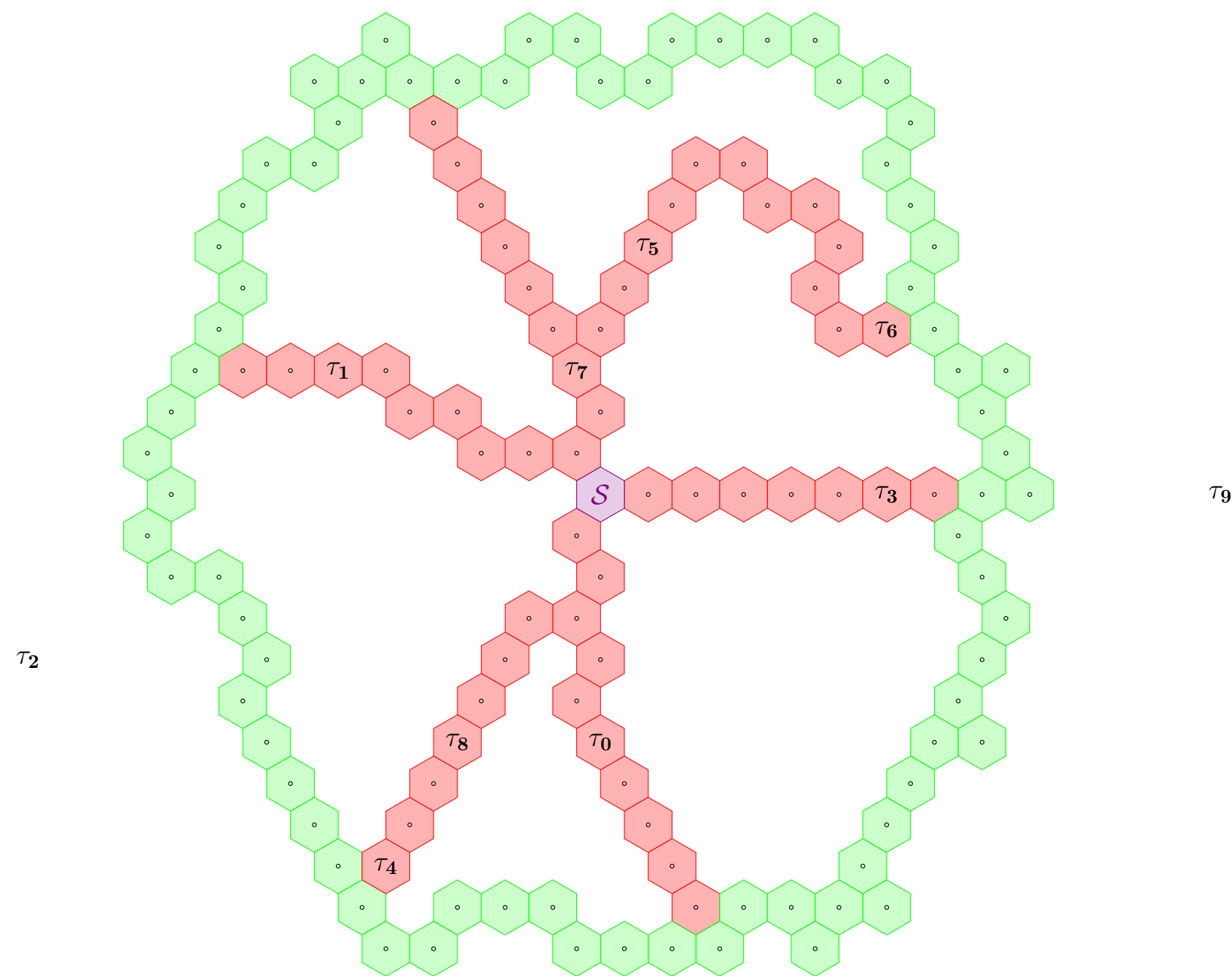
➤ **By transitivity from the previous round**

➤ **Key**

 Irremovable

 Border

 Free



➤ Round 2 - End of Balancing phase

➤ All free drones have moved to the border

➤ Autonomous movement away from the sink

➤ Connectivity is guaranteed

➤ From any point of the border

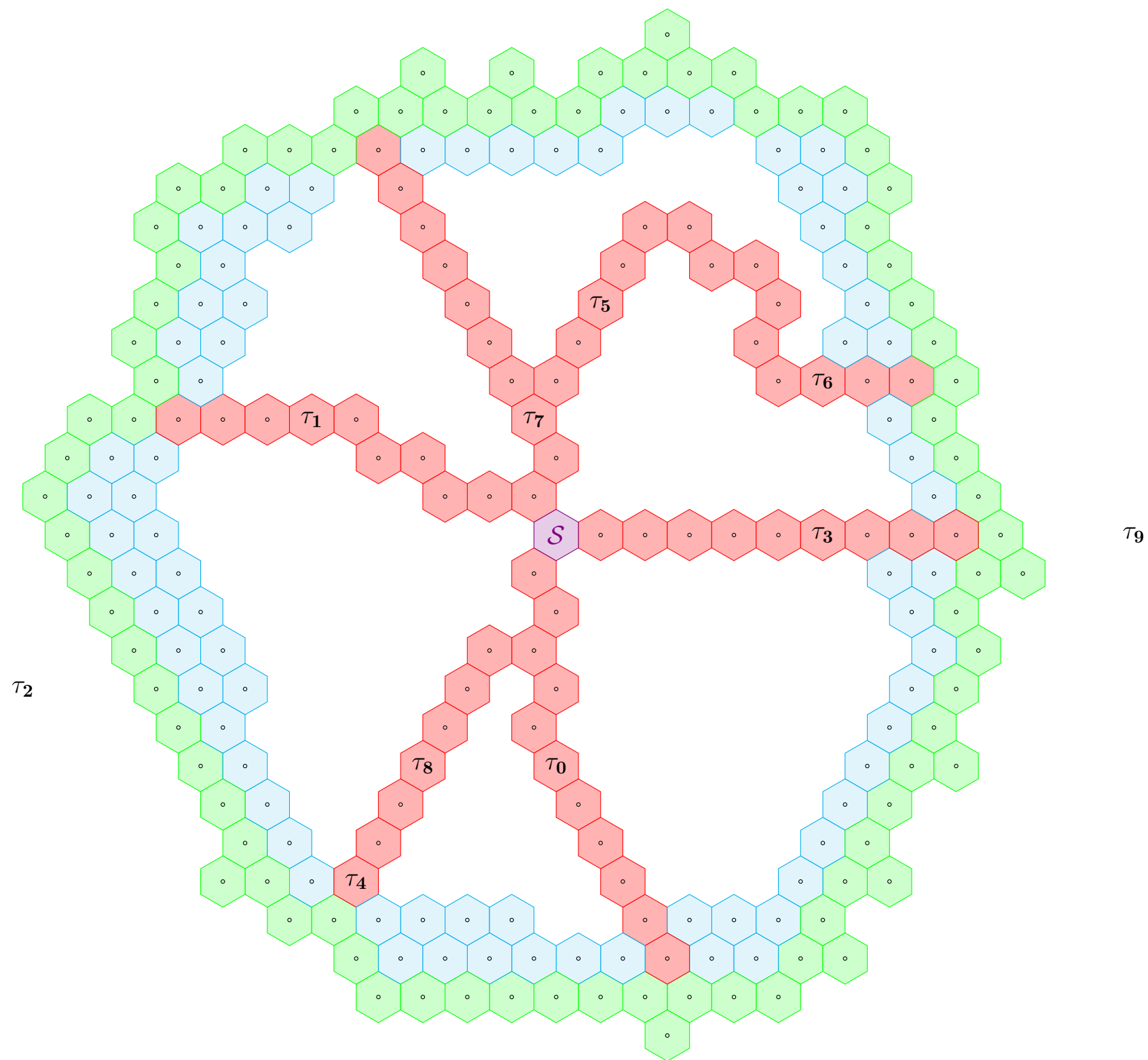
➤ and thus from any drone in the fleet

➤ Key

◻ Irremovable

◻ Border

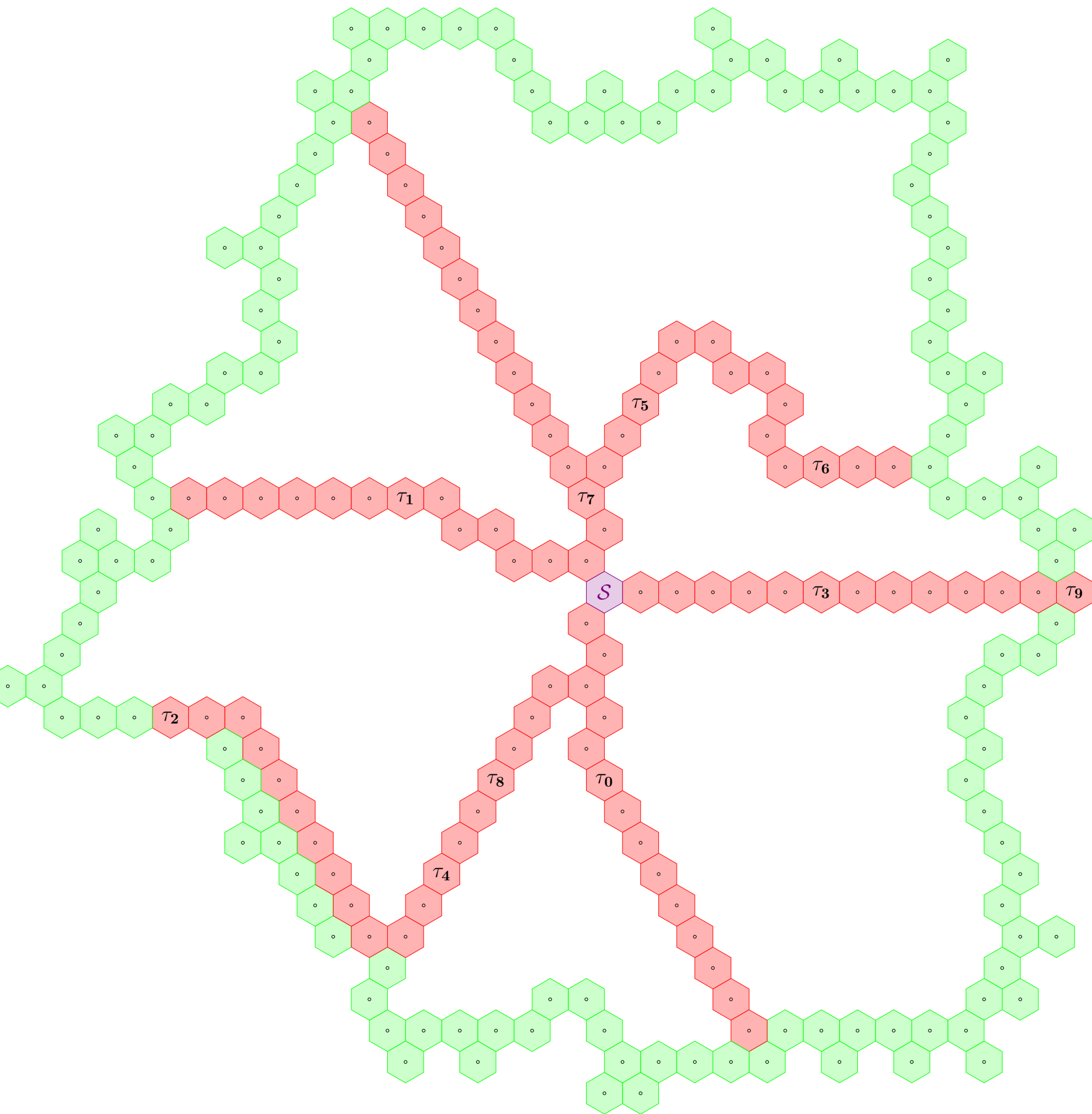
◻ Free



- **Round 3 - End of Spanning phase**
- **Area located inside the external border strictly increased**
- **Connectivity is still guaranteed**
 - By transitivity from the previous rounds

➤ Key

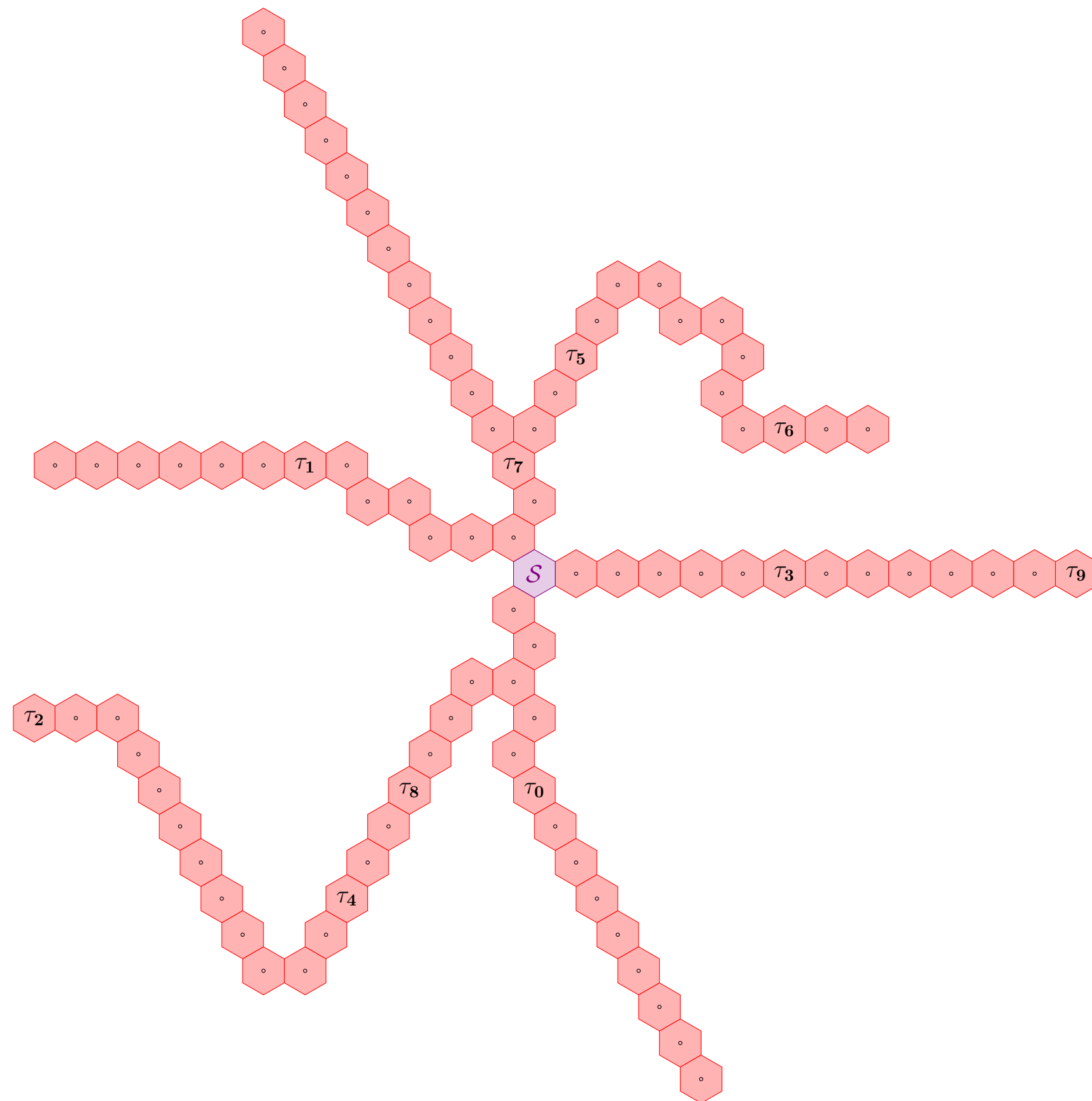
- ◻ Irremovable
- ◻ Border
- ◻ Free



- **End of the last round**
- **No more free drone is available for expansion**
- All drones are either Irremovable or on the external Border

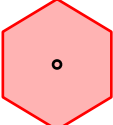
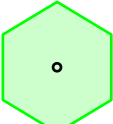
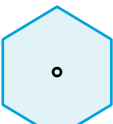
➤ Key

- ◻ Irremovable
- ◻ Border
- ◻ Free



- **End of the algorithm**
- **All non-irremovable drone are going back to the sink**
 - Remain as spare for low battery ones
- **All targets have been discovered and are connected to the sink**

➤ Key

-  Irremovable
-  Border
-  Free

- **A thorough theoretical analysis was carried out for each of the successive phases of the algorithm**
- **Each phase owns the properties of**
 - **Connectivity**
 - Guarantee that if the network is connected at the beginning of the phase, it remains fully connected at the end of the latter.
 - **Coverage**
 - Guarantee that the area explored during phases are expanding, and no non-viewed spot remains
 - **Termination**
 - Each phase eventually terminates, and termination can be detected in a distributed way
 - This ensures that a phase does not last forever, and the global algorithm also terminates eventually



PERFORMANCE EVALUATION

- **Randomly deploy targets around the sink**
 - Unknown coordinates to the drones and the sink
- **Number of targets vary from 1 to 30**
- **Number of drones from 10 to 250**
- **Communication range R_{p_i} sets to 20m**

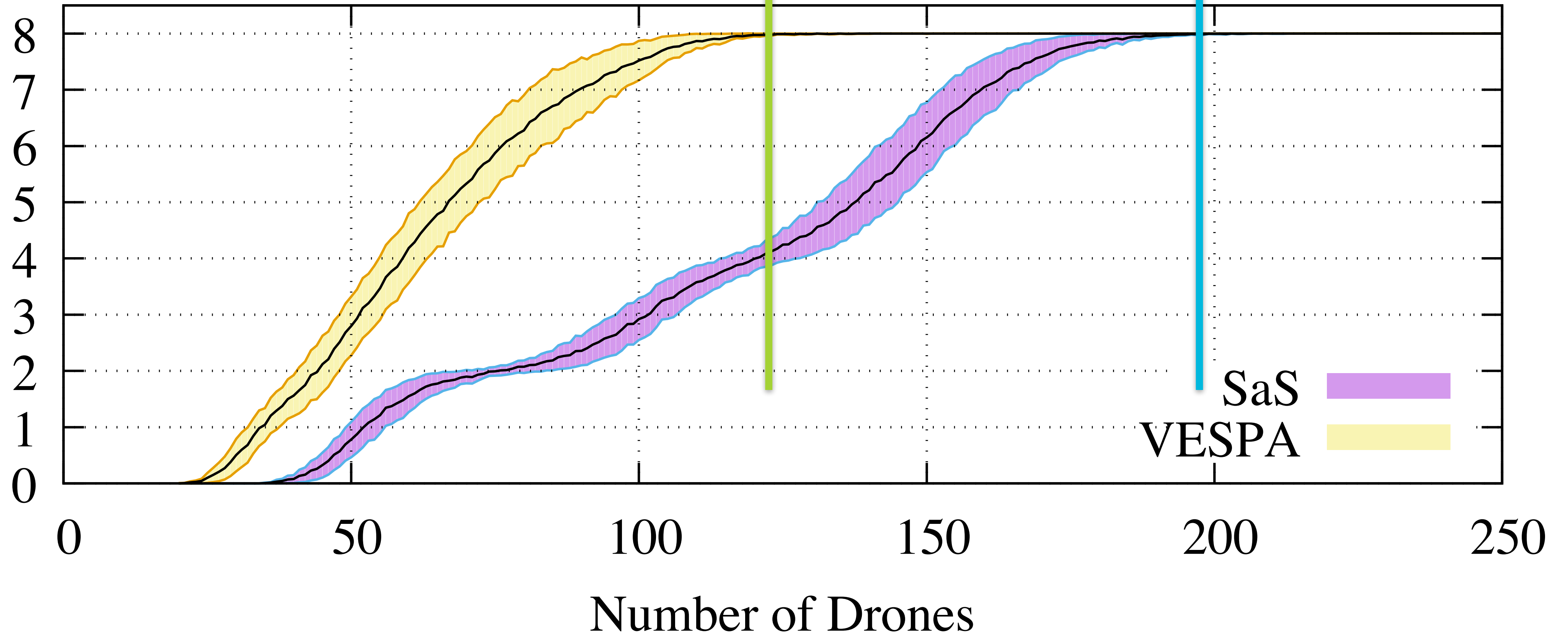
- **Comparizon with the closest related work [1]**

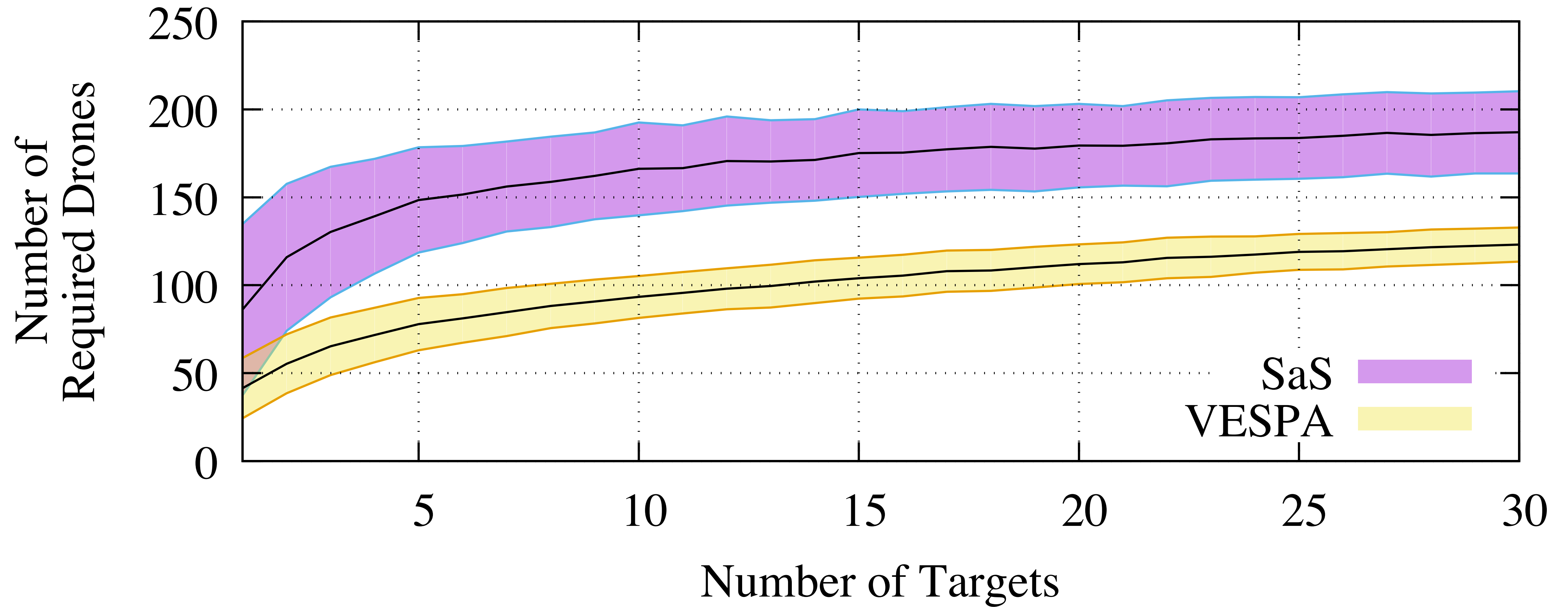
[1] T. Razafindralambo, M.Erdelj, D.Zorbas, and E.Natalizio, “*Spread and shrink: Point of interest discovery and coverage with mobile wireless sensors*”, Journal of Parallel and Distributed Computing, vol. 102, pp. 16 – 27, 2017.

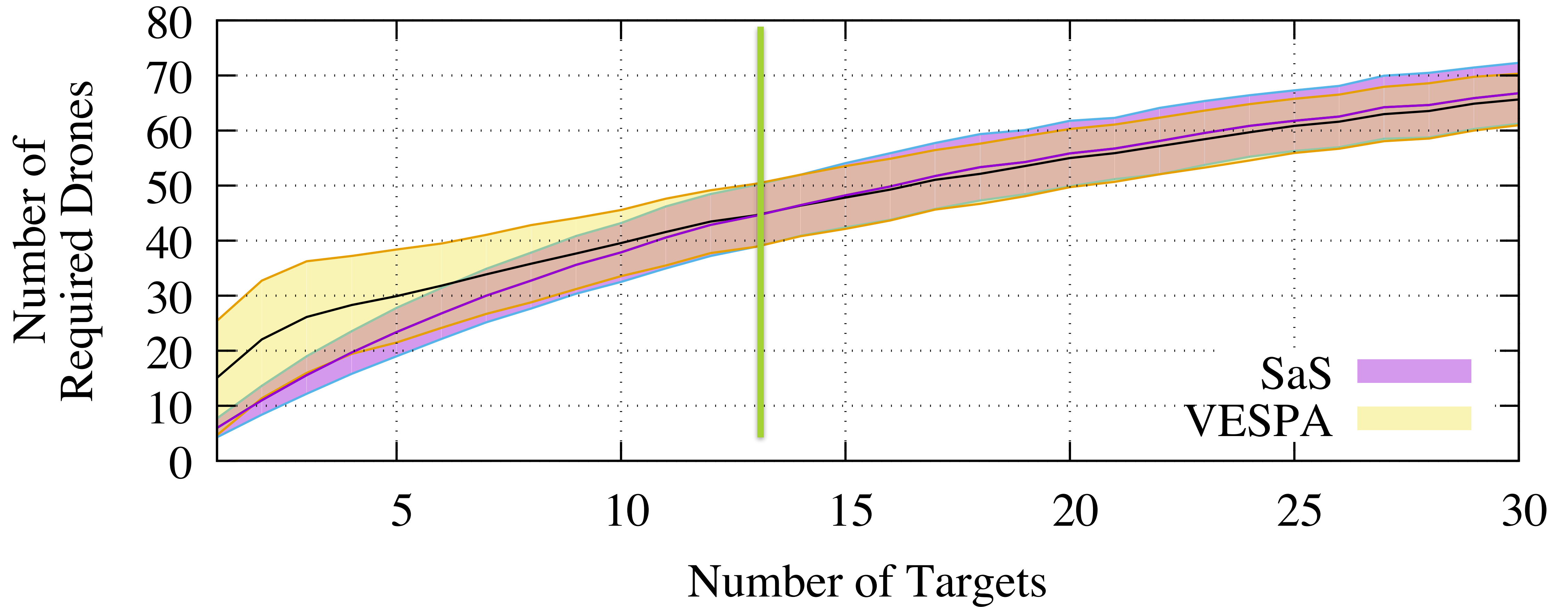
AVERAGE NUMBER OF DISCOVERED TARGETS

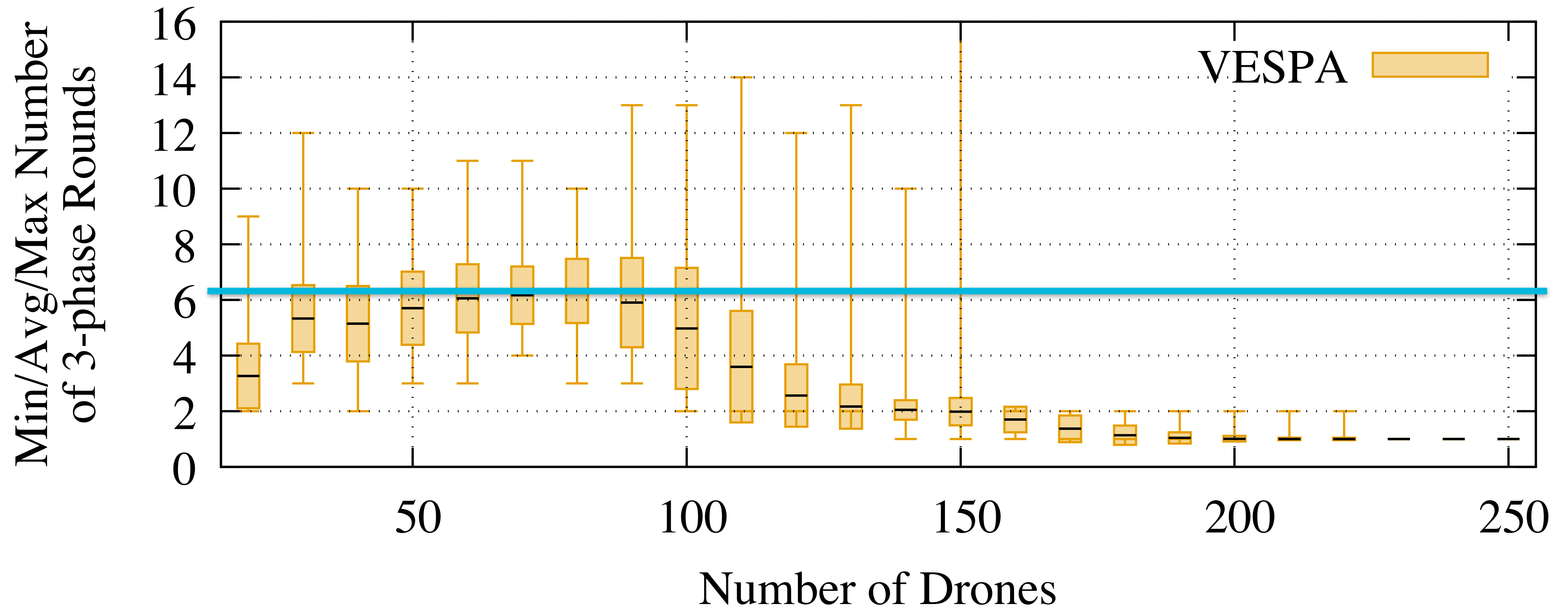
— 8 TARGETS LOCATED IN SQUARE AROUND THE SINK

Number and Variance
of Discovered Targets









CONCLUSION OF THE CHAPTER

- Proposition of VESPA in a multi-hop UAV wireless network
 - Distributed algorithm using only one-hop information
 - Discover targets with unknown location
 - Auto-organize themselves to ensure connectivity between them and the sink
- Theoretical proofs
 - Connectivity and coverage are preserved during all stages
 - All phases eventually terminate
- Performance evaluation
 - outperforms the state of the art, both in terms on number of drones used in the solution and number of discovered targets



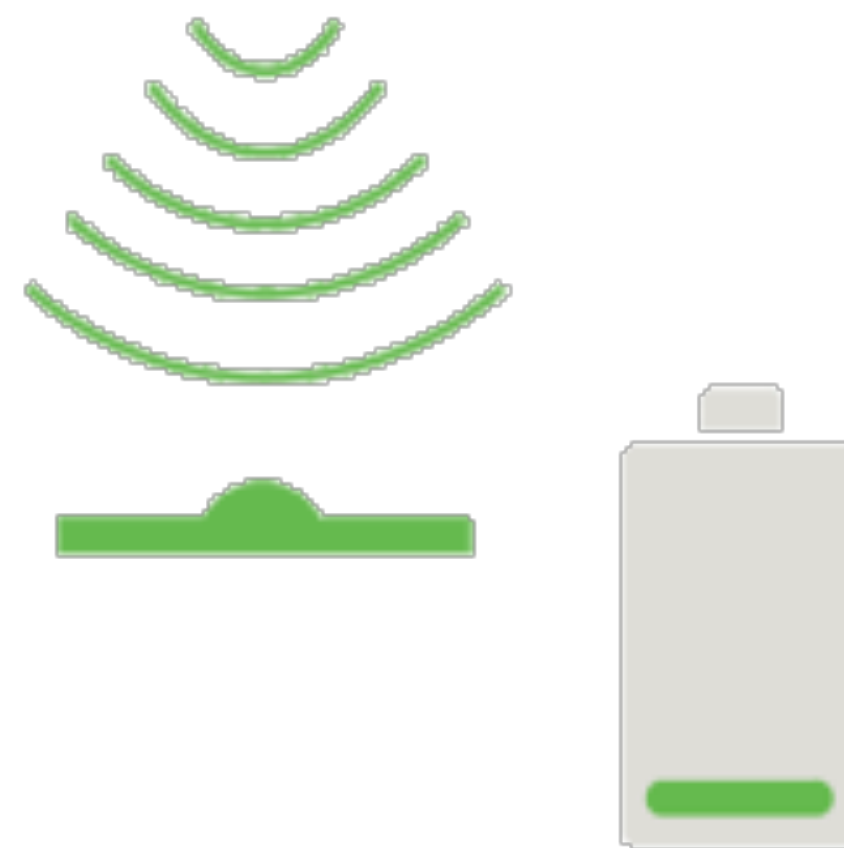
AUTONOMOUS FLEET OF DRONES FOR EXTENDING THE LIFESPAN OF AN IOT NETWORK



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Igor Dias Da Silva, Yann Busnel, Christelle Caillouet.
Trajectory Optimization for Fast Sensor Energy Replenishment using UAVs as RF sources.
Submitted to 2022 IEEE Global Communications Conference (GLOBECOM),
Rio de Janeiro, Brazil, December 2022

HOW TO CHARGE A COLLECTION OF SENSORS USING A FLEET OF DRONES WITH RF HARVESTING?



➤ Democratisation of the IoT

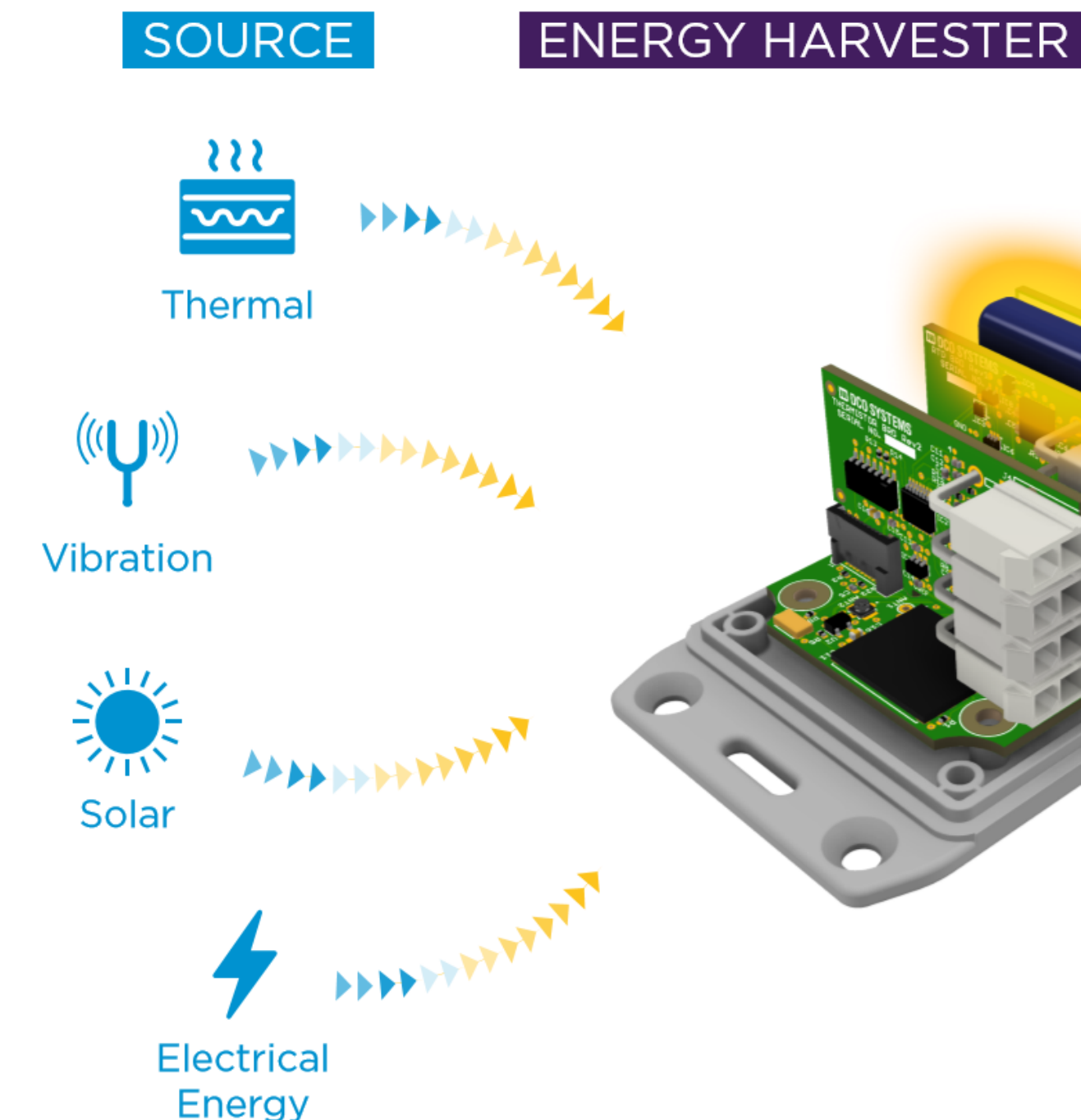
- Fast expansion
- Large set of usecases
 - industry 4.0
 - military
 - home automation
 - ecology
 - precision agriculture
 - disaster management
 - etc.

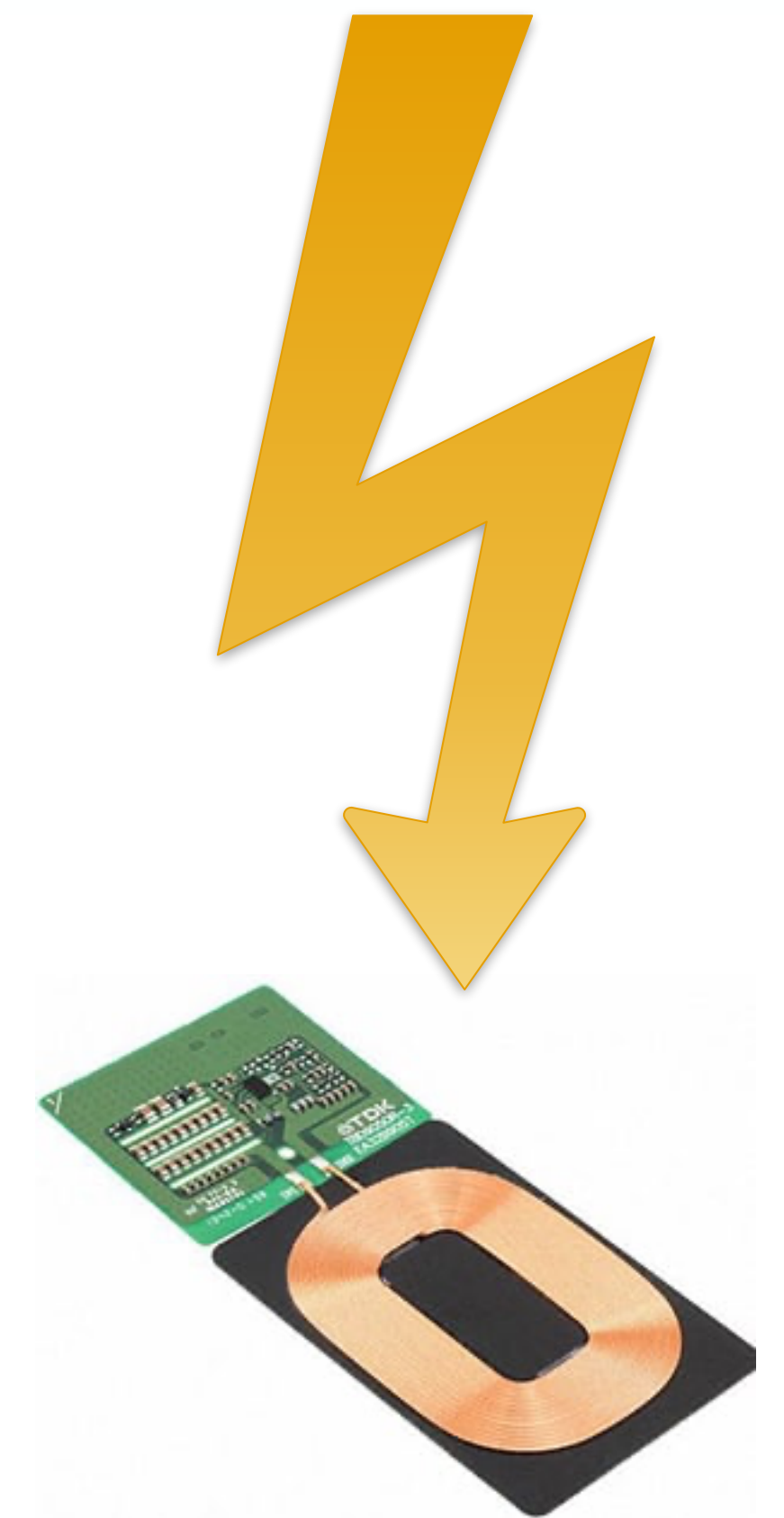
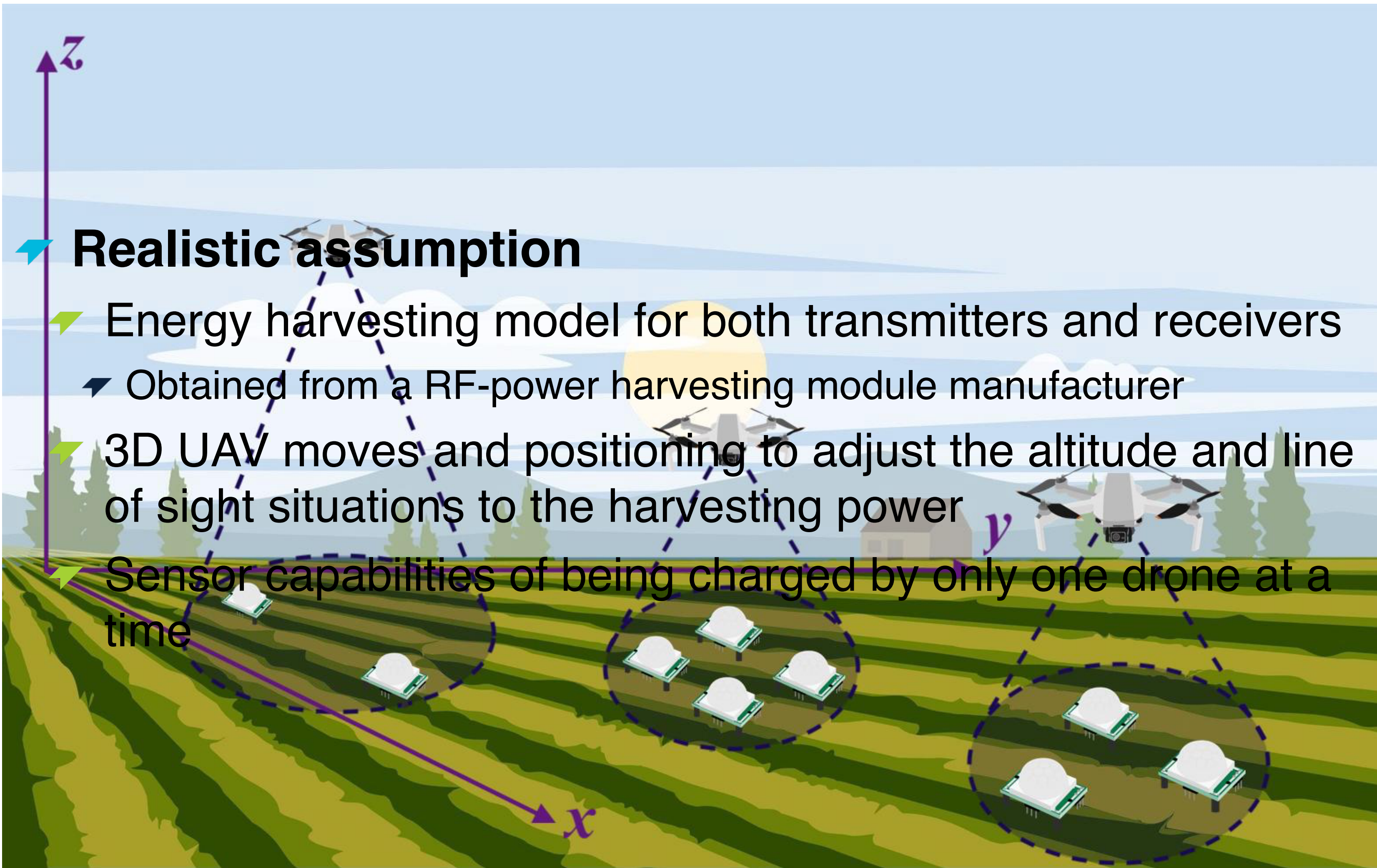
➤ Require the implementation of sensor systems over long periods of time

- Optimising the lifetime of each sensor is a key element

➤ Regular recharging is paramount

- Large scale
impossible for human
- Small size
no local production unit
- Possible closed areas
*large warehouses
or assembly lines*





➤ **Extend existing works in the following way :**

➤ Fleet of drones

- Most of the works limit their study to deploying only one drone in the sensor network

➤ 3 dimensional space

- Studies are often limited in a two-dimensional space

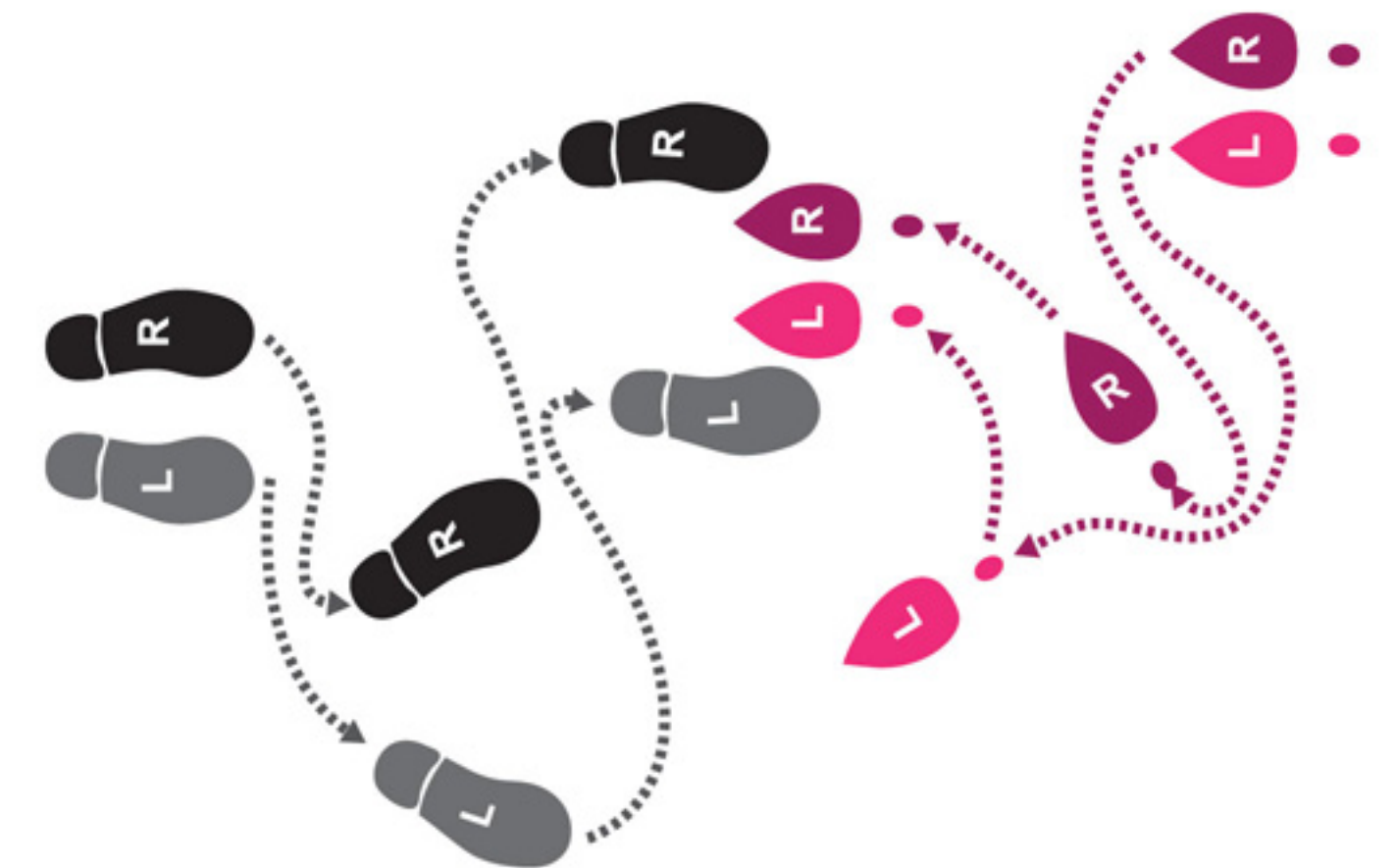
➤ Adaptability and scalability

- Some works focus on one-to-one recharge model in which one drone is dedicated to one sensor
- The scenarios either require as many drones as sensors or energy harvesting relaying capabilities, and get rid of the flying robots mobility and high-power omni-directional energy emission

➤ A two-step optimization framework to determine the UAVs trajectories

- Mixed Integer Linear Program (MILP) to optimise both the placement of the UAVs and the associated hovering times
- A greedy algorithm to schedule the flight plans, integrating spatiotemporal constraints and positioning conflicts

➤ **Output:** a set of UAV conflict-free trajectories fulfilling the positions computed by the MILP, while minimizing the overall duration for recharging the whole system.



ENERGY HARVESTING MODEL

Amount of power harvested by a sensor : $P_{h_s} = P_{rx}^{d_{us}} f^{d_{us}}$
- f is the efficiency of the harvesting antenna at distance d_{us}

Received power at distance d : $P_{rx}^d = P_0 \frac{e^{2\sigma G}}{d^{2b}}$
- log-normal distribution with a shadowing coefficient σ
- P_0 is the received power at reference distance

Harvested energy of a sensor s for a given time period t : $H_s^t = \int_0^t P_{h_s} t dt.$

Objective:

Determine the optimal number of drones needed to recharge the sensors in the minimum amount of time.

2 main variables for UAV positioning:

- one binary variable $y_p^u = 1$ if the drone u is deployed at position $p \in P$
- one continuous variable t_p^u representing the time duration of u at $p \in P$

OPTIMAL POSITIONING : MILP APPROACH

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- one continuous variable t_p^u representing the time duration of u at $p \in P$

$$\min \max_{u \in U} \sum_{p \in P} t_p^u$$

$$\min \max_{u \in U} \sum_{p \in P} y_p^u$$

Define 2 continuous variables modeling

- the worst time λ_1
- the worst number of positions λ_2

$$\sum_{p \in P} t_p^u \leq \lambda_1, \forall u \in U$$

$$\sum_{p \in P} y_p^u \leq \lambda_2, \forall u \in U$$

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$$\sum_{p \in P} y_p^u \leq \lambda_2, \forall u \in U$$

$$\sum_{u \in U} t_p^u + \sum_{p' \in P, (x_p, y_p) = (x_{p'}, y_{p'})} \sum_{u' \in U} t_{p'}^{u'} \leq \lambda_1, \forall p \in P$$

$$\sum_{u \in U} \sum_{p \in P_i} t_p^u \leq \lambda_1, \forall s \in S$$

$$\sum_{u \in U} x_u \leq B$$

$$\sum_{u \in U} \sum_{p \in P_i} (1 - \eta) H_s^{t_p^u} \geq E_s, \forall s \in S$$

$$\sum_{p \in P} t_p^u \leq \tau x_p, \forall u \in U$$

$$t_p^u \leq \tau y_p^u, \forall u \in U, p \in P$$

$$x_u \leq \sum_{p \in P} y_p^u, \forall u \in U, p \in P$$

$$y_p^u \leq x_u, \forall u \in U, p \in P$$

Objective:
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$$\sum_{p \in P} t_p^u \leq \lambda_1, \forall u \in U$$

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➤ **We can combine the bi-objective into only one function** $\min a \cdot \lambda_1 + (1 - a) \cdot \lambda_2$
 ➤ where a is an input parameter to balance the impact of the two objective functions

➤ **Take into account the following constraints**

- Number of used drones do not exceed the budget B
- Harvested energy of each sensor s must be fulfilled
- Total length of UAVs flying time cannot exceed the imposed time limit
- Not any drone can be placed above or under another one simultaneously
 - Limit physical collisions between the drones as well as interference
- Limit the total time spent on the set of charging positions P_s of sensor s to the longest flying time of a drone

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EXAMPLE USING 2 ALGORITHMS TO SCHEDULE THE TASKS IN A 5X5 GRID WITH 40 SENSORS AND 4 DRONES

➤ Output : a set of tasks, where a task k is given by

- a drone u_k
- a position p_k
- a duration t_k in seconds
- a set of sensors S_k that are charged during the task's execution

Tasks by drone

$d_0 = [0, 1, 2]$
 $d_1 = [3, 4, 5]$
 $d_2 = [6, 7, 8]$
 $d_3 = [9, 10, 11]$

Sensors by task

0 = [35, 9, 18, 34, 26, 17, 12, 19]
1 = [5, 13, 23, 1, 25, 28, 39, 22, 37, 27, 29, 32, 1]
2 = [13, 23, 3, 25, 28, 8, 19, 36, 14]
3 = [35, 0, 18, 34, 26, 17, 15, 12]
4 = [10, 0, 38, 15, 4]
5 = [35, 9, 18, 21, 26, 17, 2]
6 = [5, 11, 13, 23, 1, 3, 25, 28, 27, 8, 19, 36, 32, 14]
7 = [10, 0, 38, 34, 15, 12]
8 = [35, 9, 18, 21, 26, 17, 2]
9 = [11, 31, 16, 30, 7, 6, 33, 24, 14]
10 = [5, 13, 23, 1, 25, 28, 39, 22, 27, 29, 36, 32]
11 = [20, 16, 30]

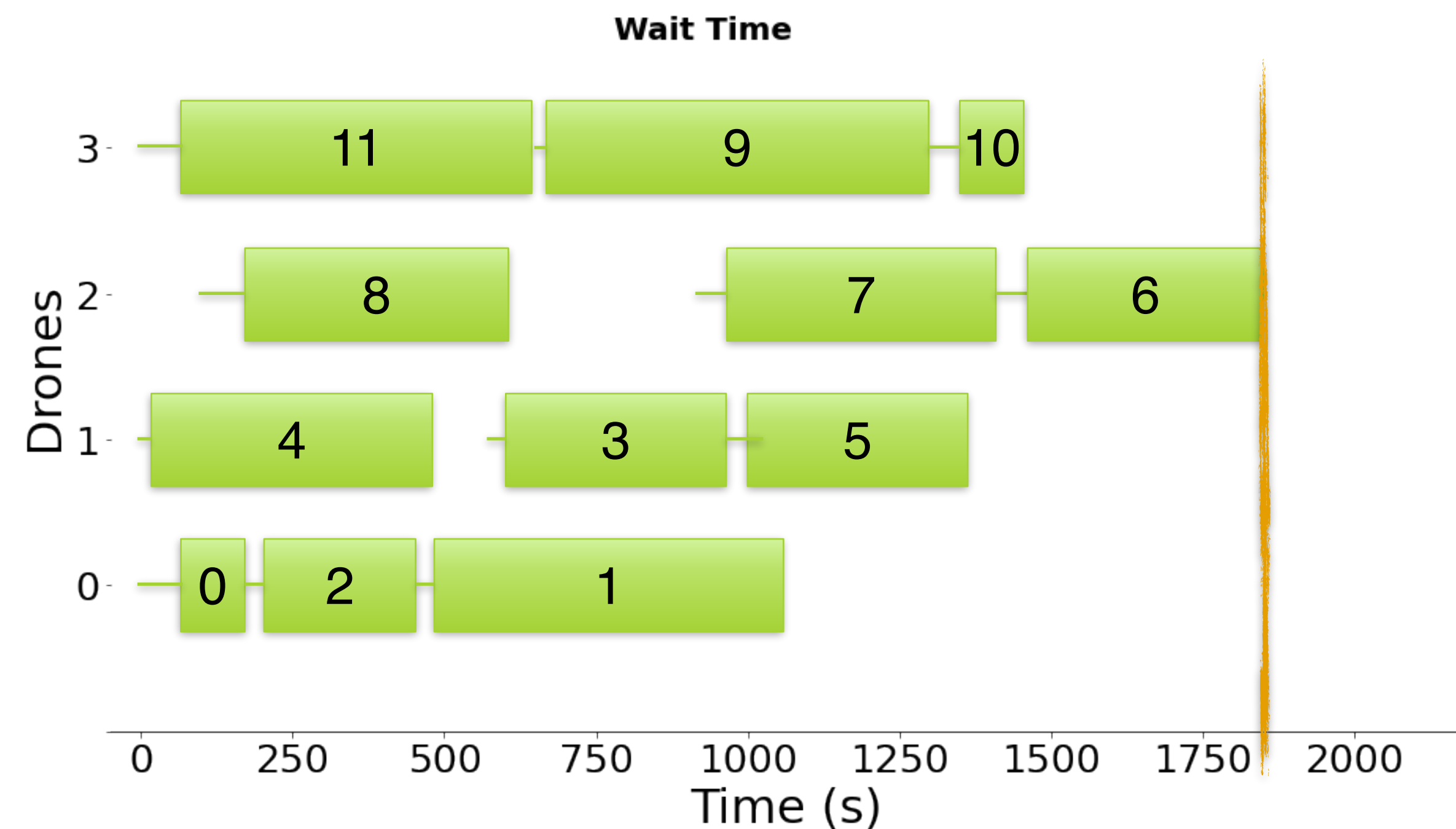
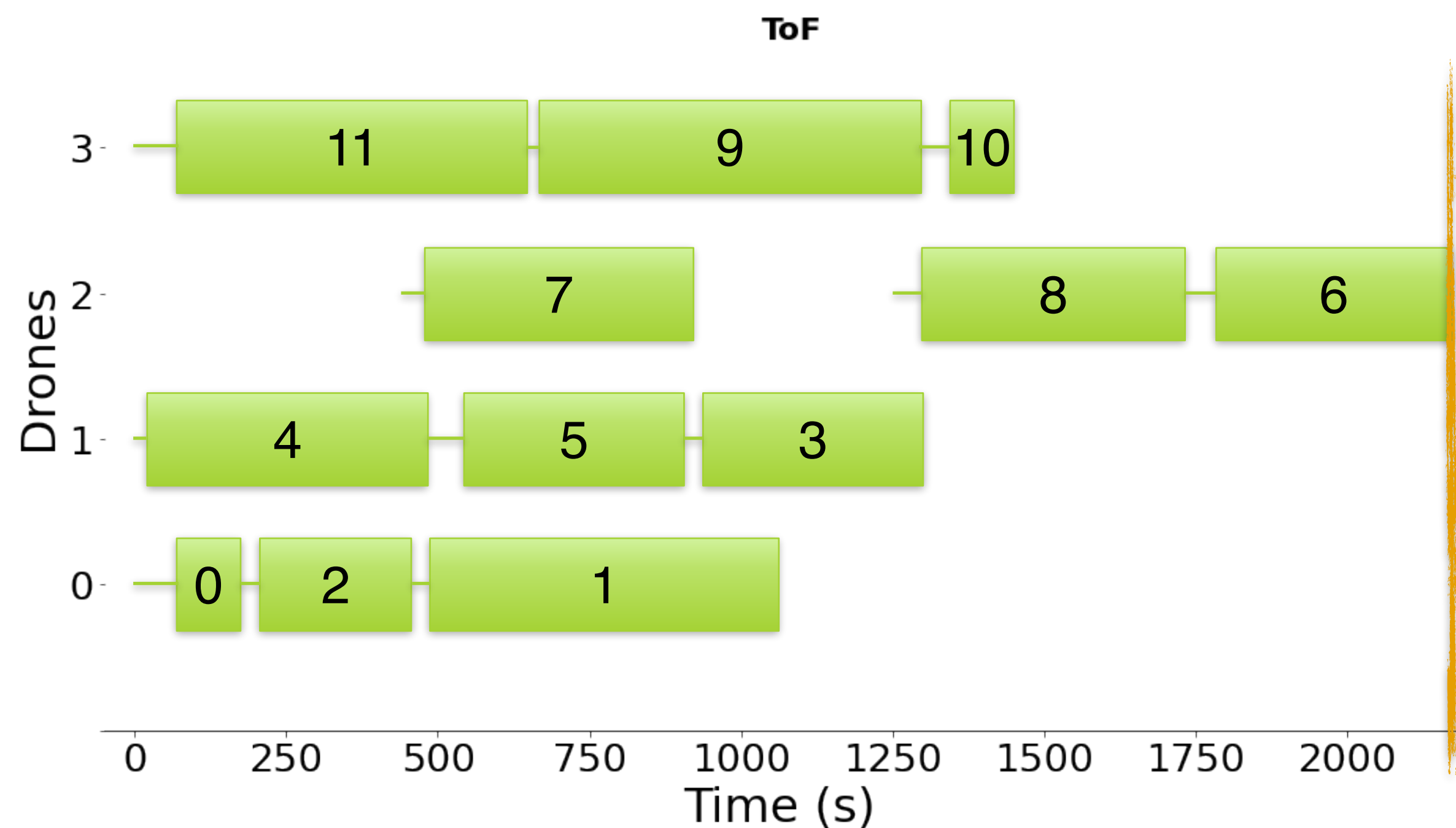
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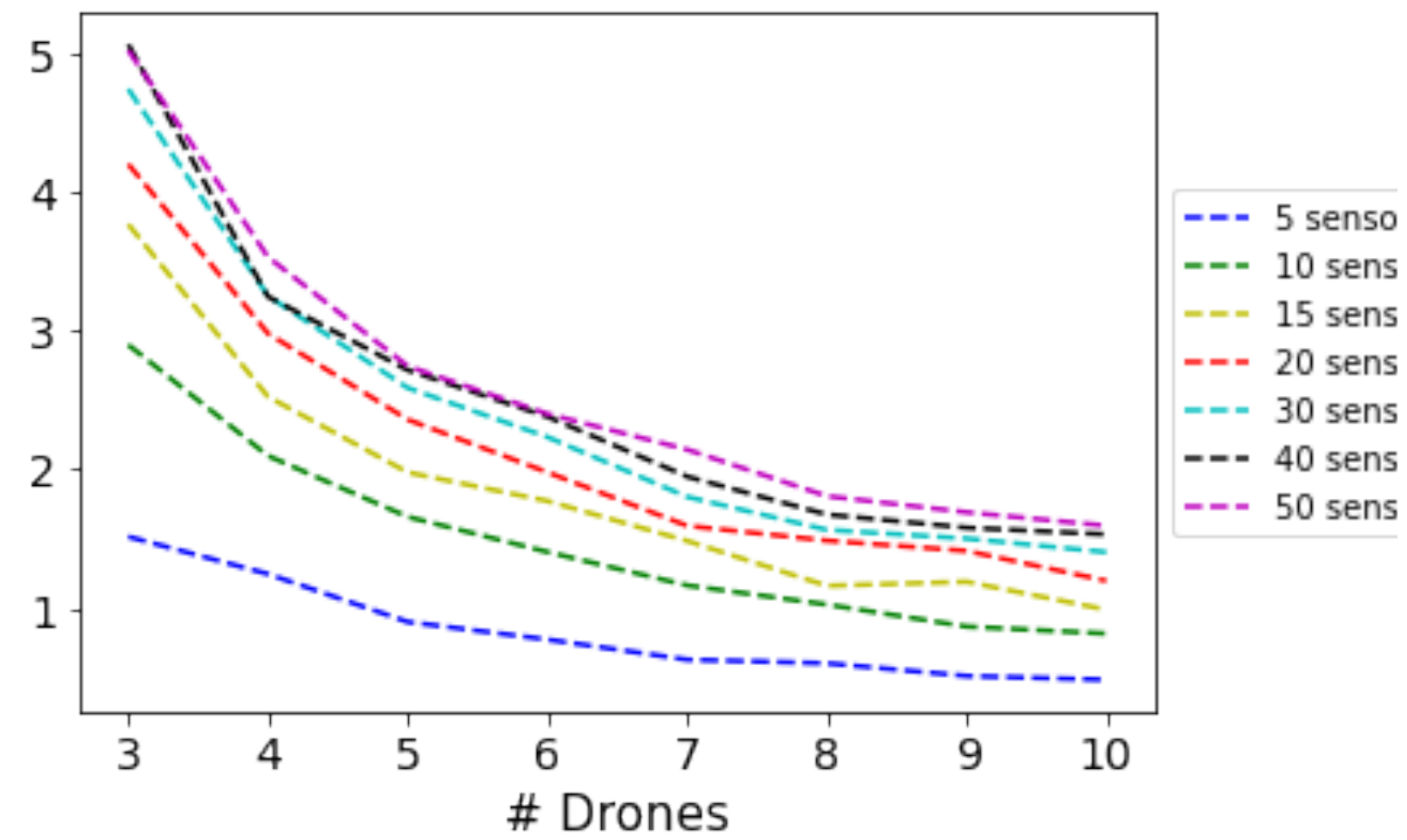
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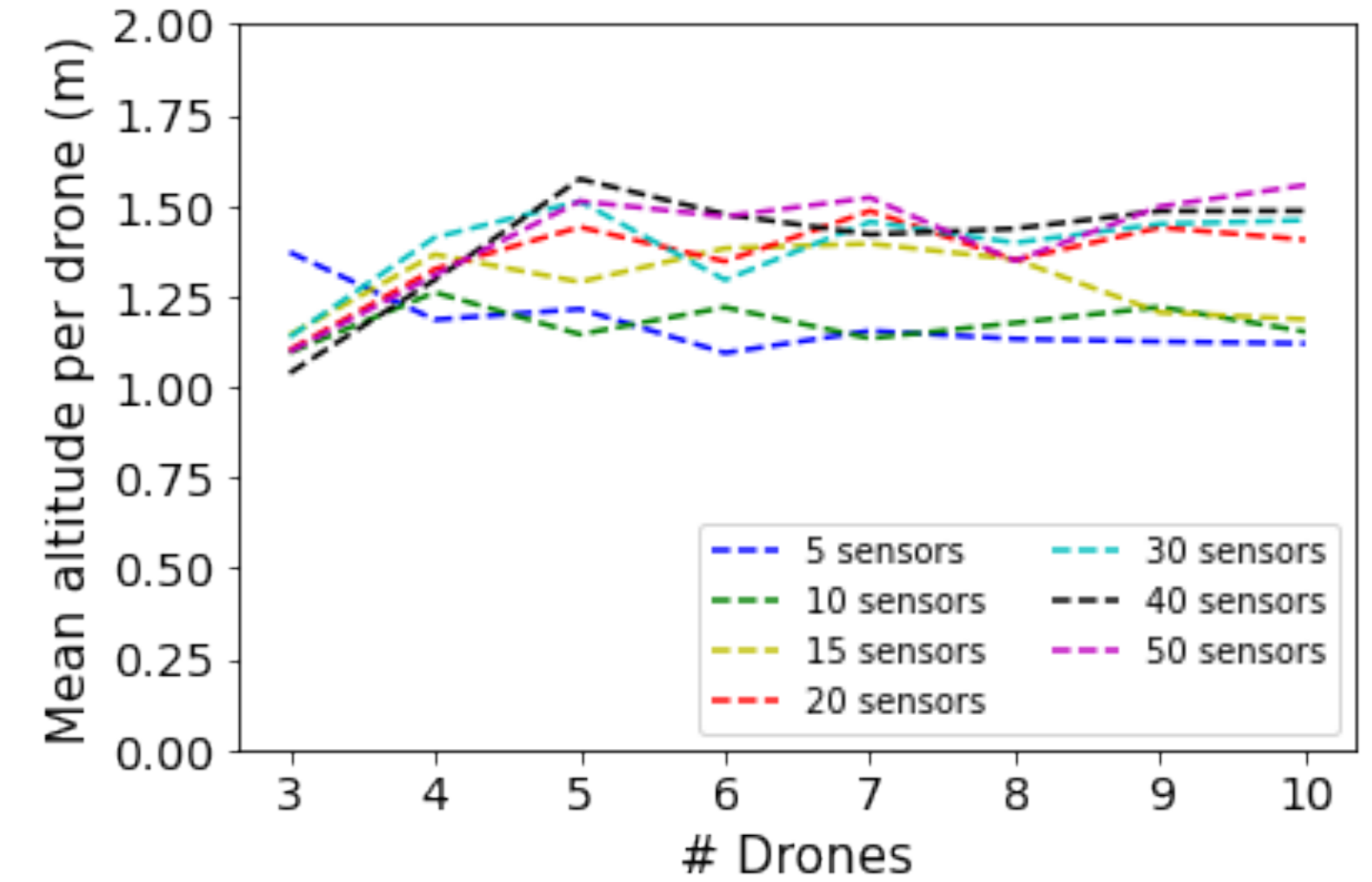


PERFORMANCE EVALUATION MILP

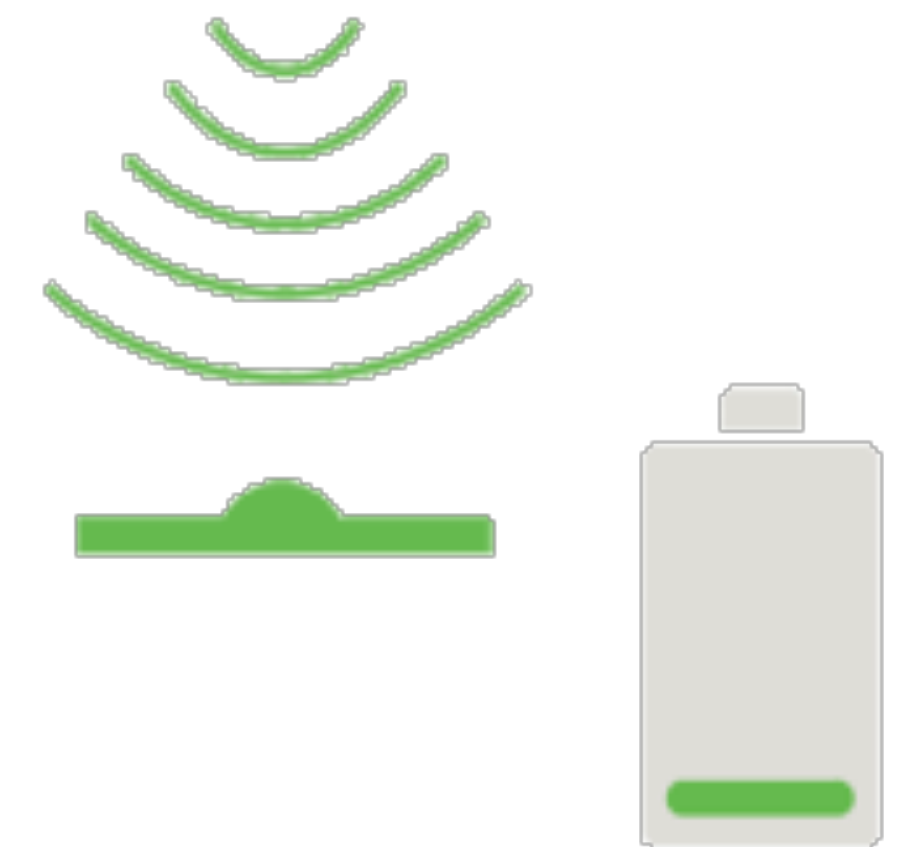
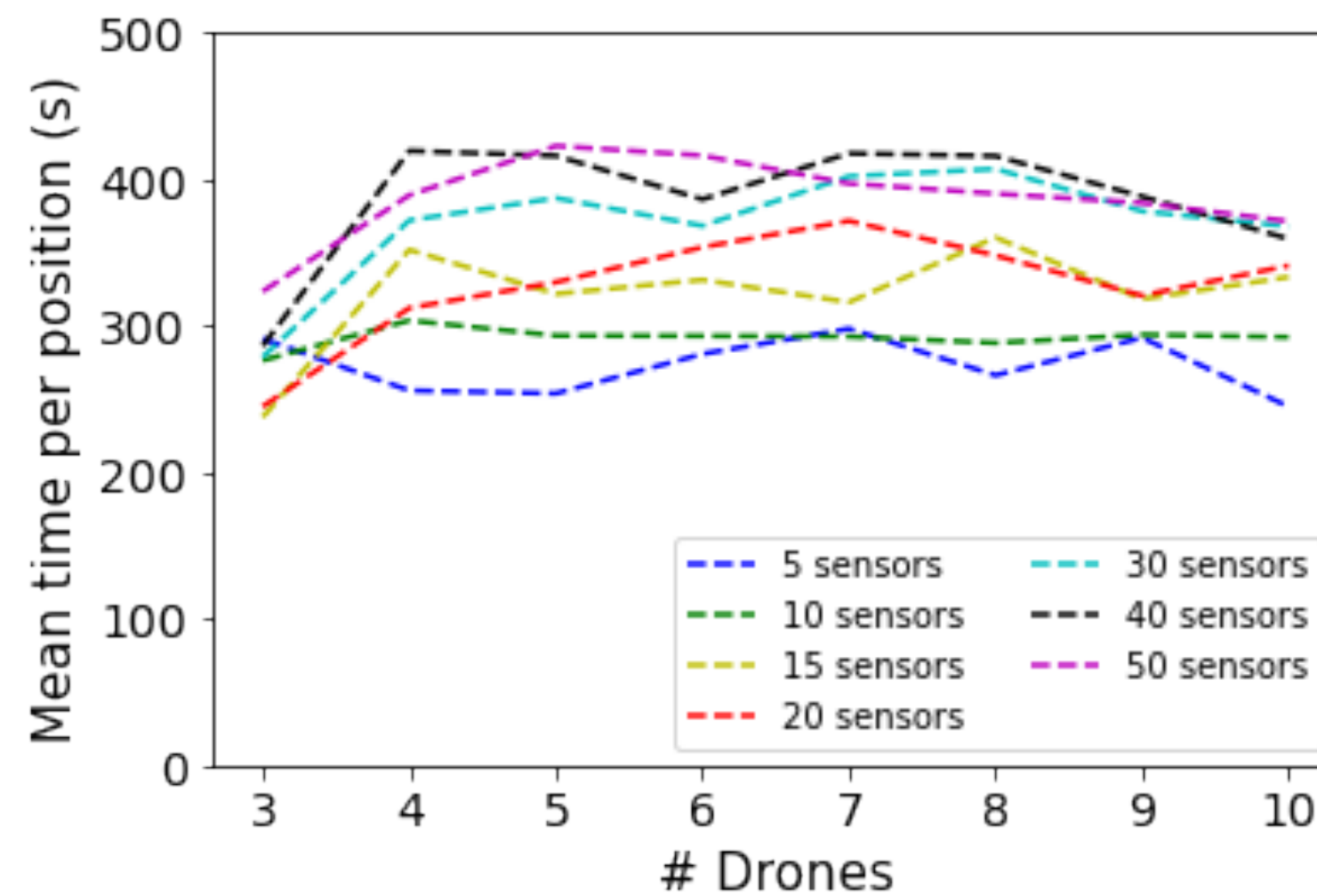
Mean number of positions each drone



Mean altitude of the positions occupied

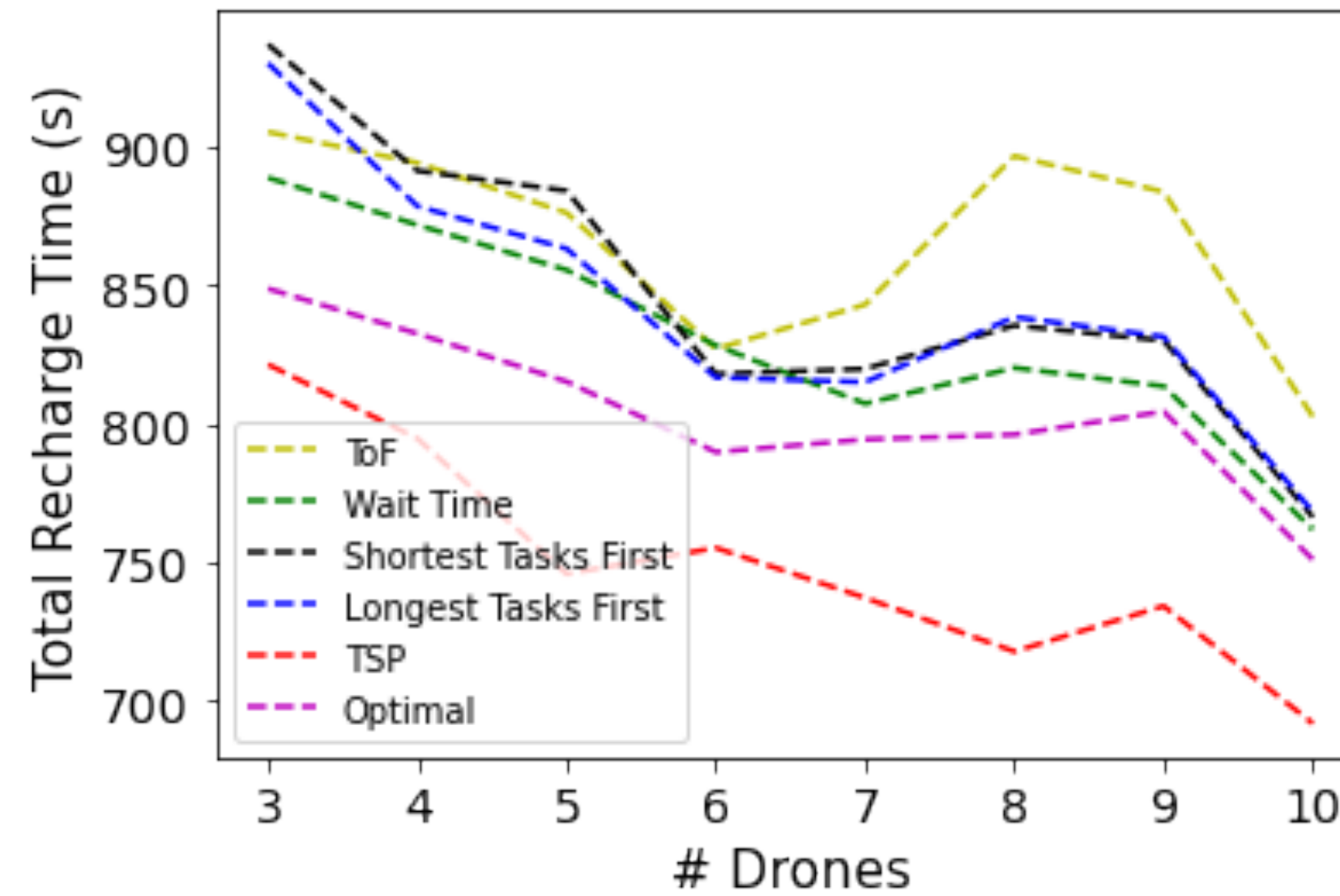


Mean time spend at the same positions

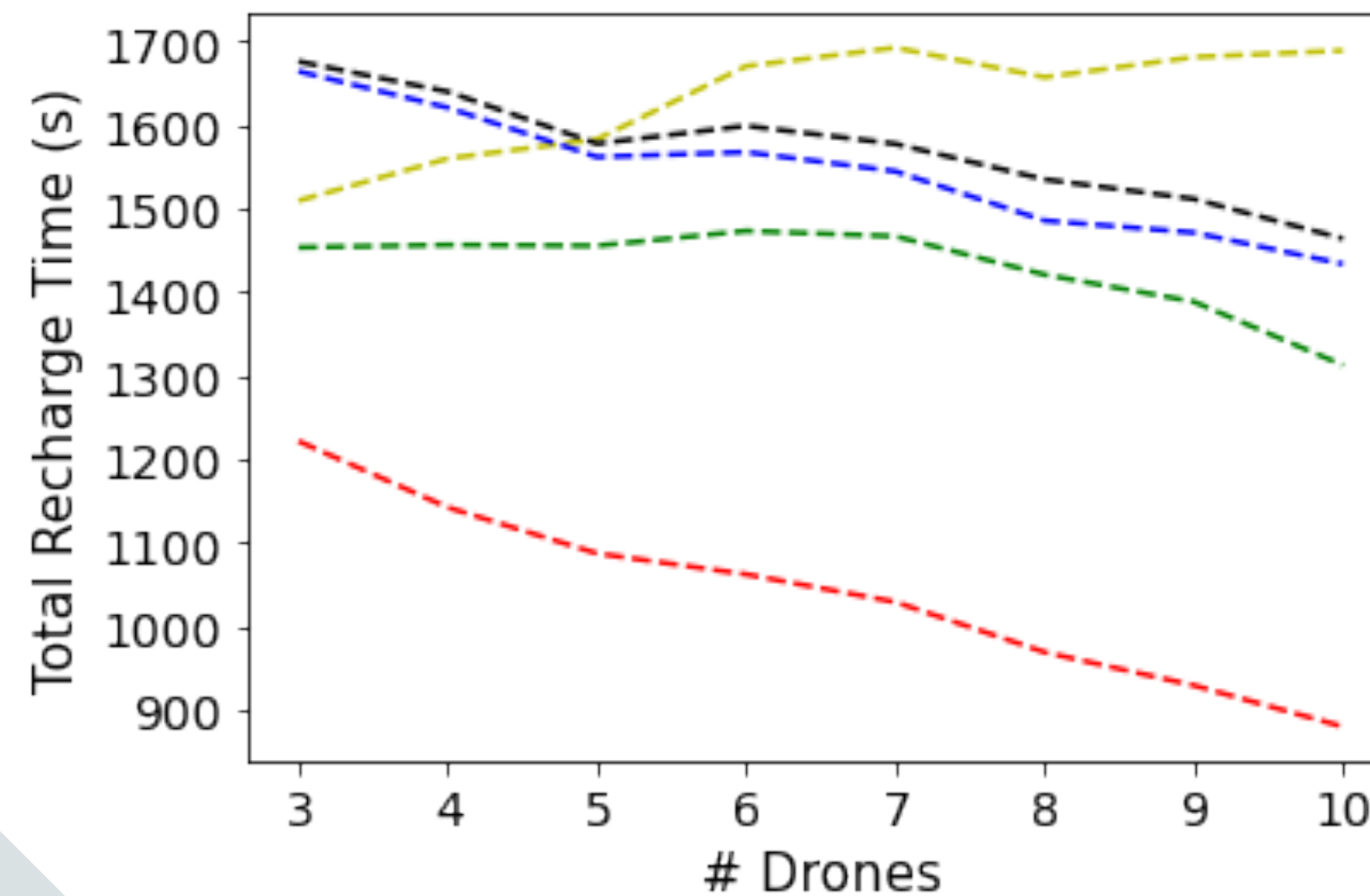


PERFORMANCE EVALUATION SCHEDULING

Total recharge time: 870 scenarios with < 10 tasks and $5 \leq \text{sensors} \leq 15$



Total recharge time for all 2800 scenarios.
Optimal cannot be depicted





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*ÉCOLE D'ÉTÉ RESCOM DE
RECHERCHE DU GDR RSD - 28/06/22*

**THANKS FOR
YOUR ATTENTION**

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