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

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Bretagne-Pays de la Loire  
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# DRONE FLEET COORDINATION

*HOW SELF-ORGANISATION  
SOLVES ALL YOUR PROBLEMS*

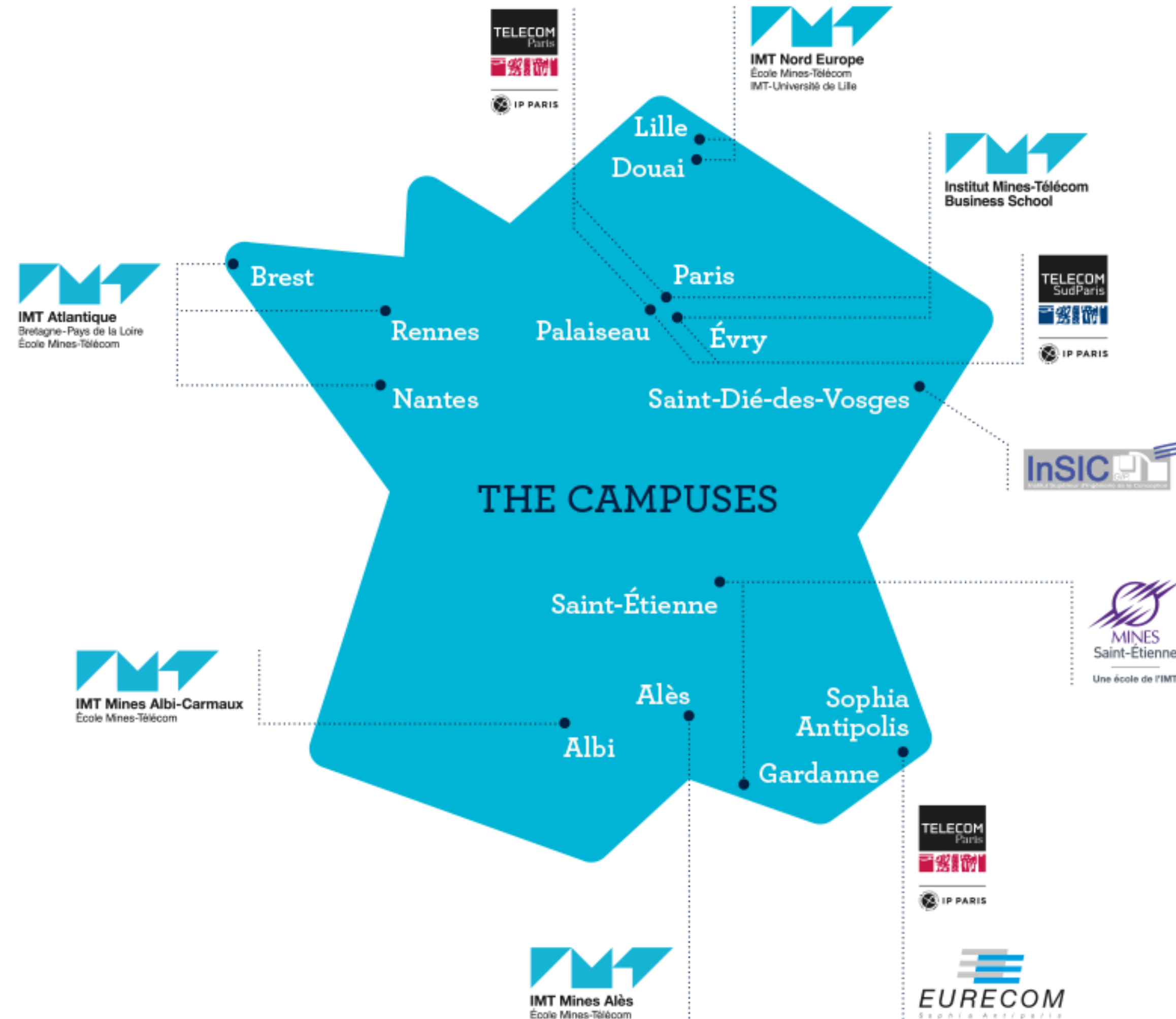
***YANN BUSNEL***

*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

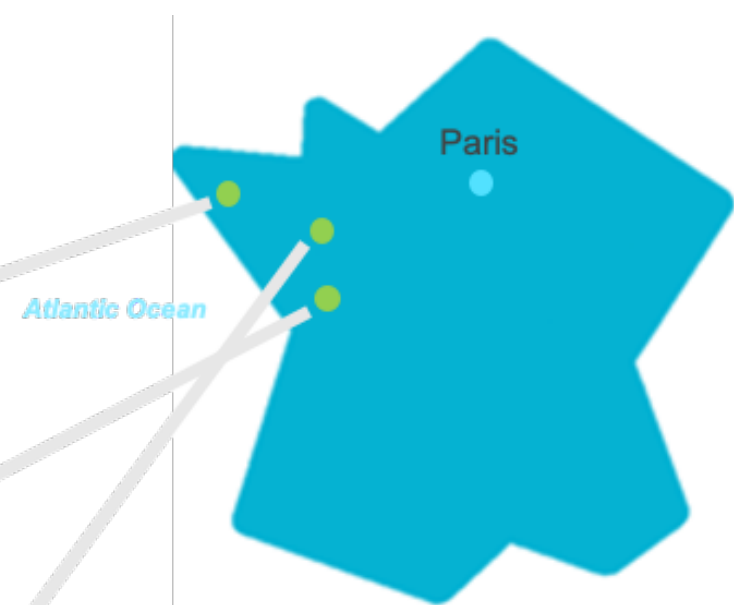


#Digital technology

#Energy

#Environment

## 3 CAMPUSES



Brest



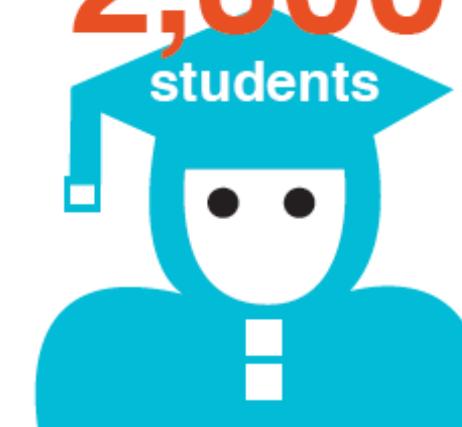
Nantes



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](#)

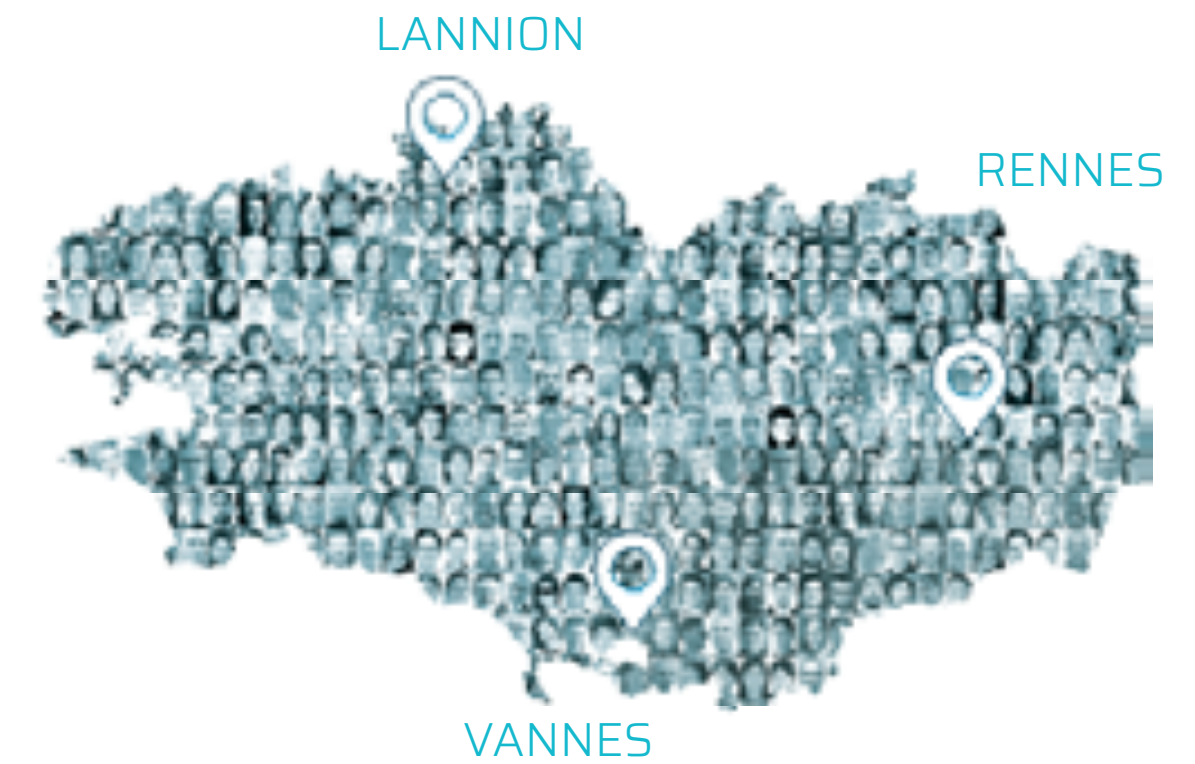
# WHAT IS IRISA?



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



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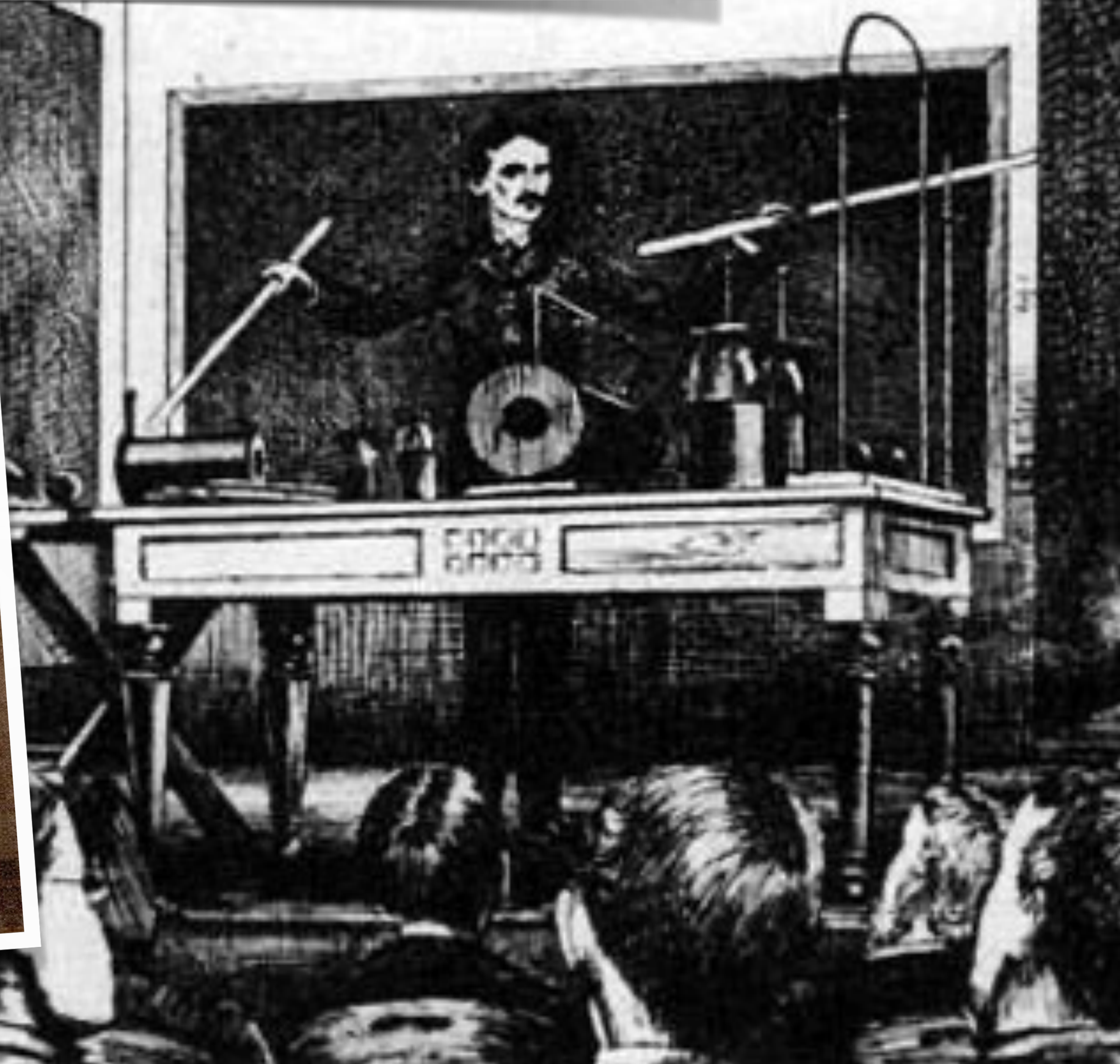
- **July 1849**
- **Austrians launched around two hundred pilotless balloons against the city of Venice**
  - Each carrying a 24- to 30-pound bomb
  - Austrians used smaller pilot balloons to determine the correct fuse settings



	Time period	Institution	Iconic Drone	Usage
Phase 1 Target drone				the dummies
Phase 2 Flying bomb drone				ordinance enemy lines
Phase 3 Surveillance				inied or areas
Phase 4 Hunter-Killer				nhunt » r of terror
Phase 5 Police drone				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
- ...



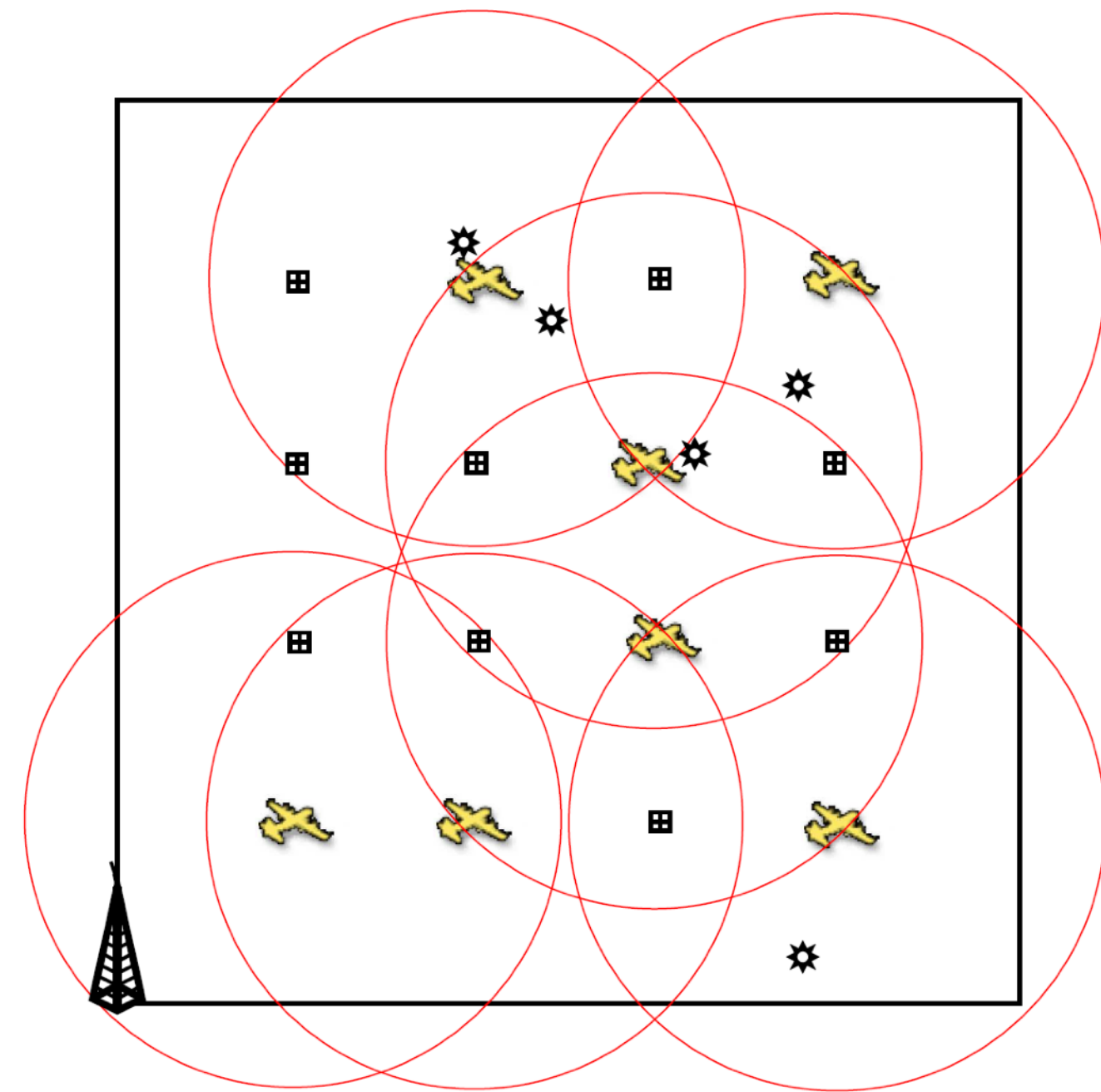
# OBJECTIVES





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

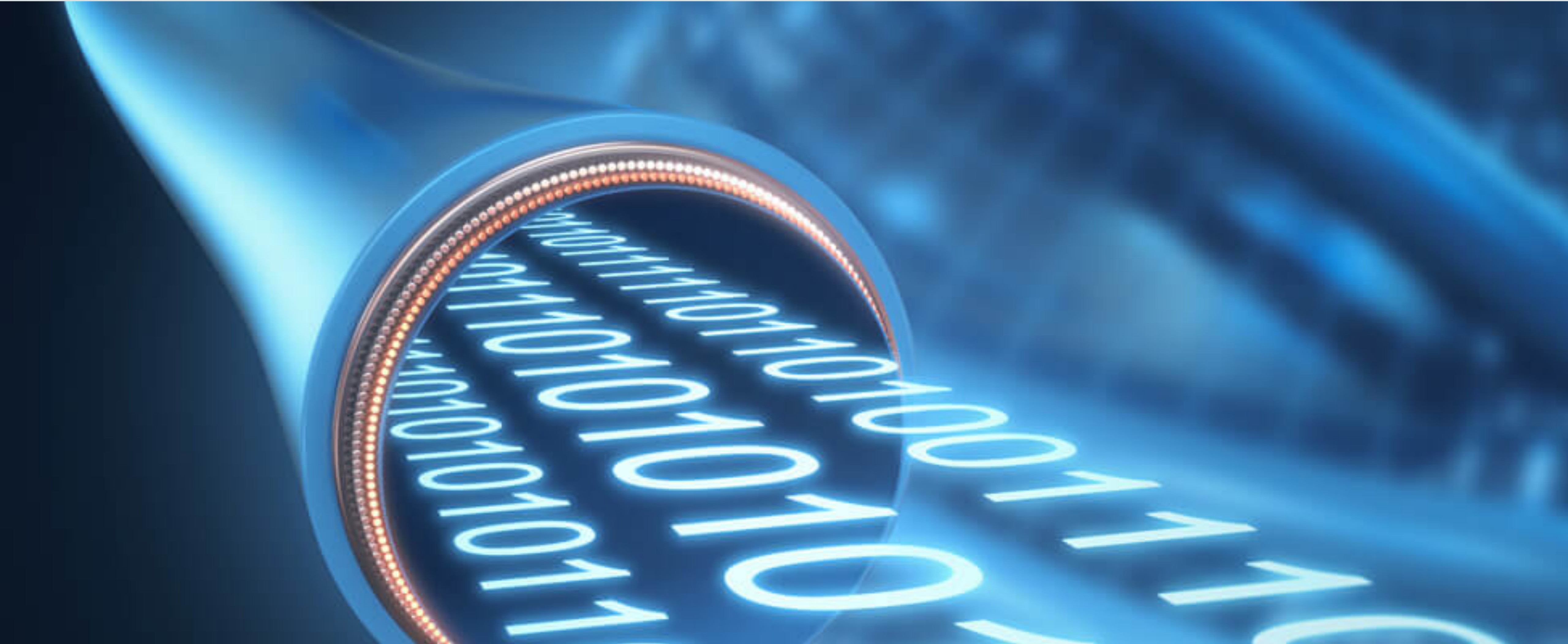
## 2. Large scale deployment

- 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**



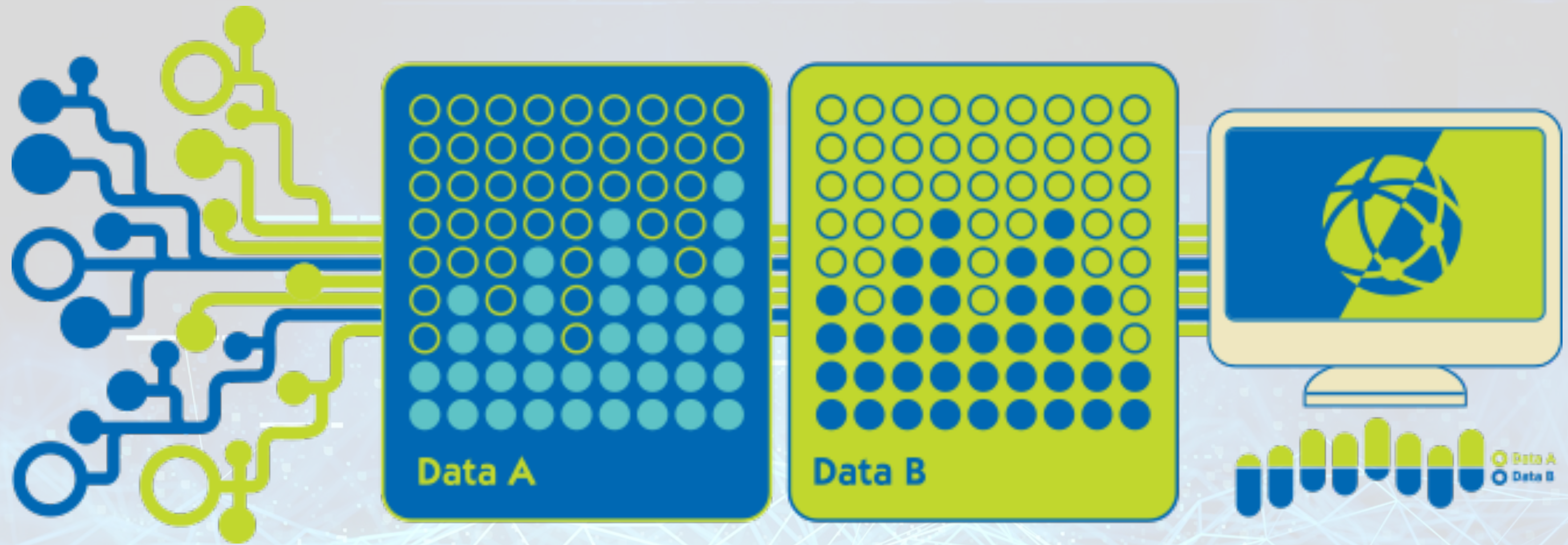


## ➤ Sketching techniques

- 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**

➤  $(\epsilon, \delta)$ -additive-approximation of  $m_i$

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

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

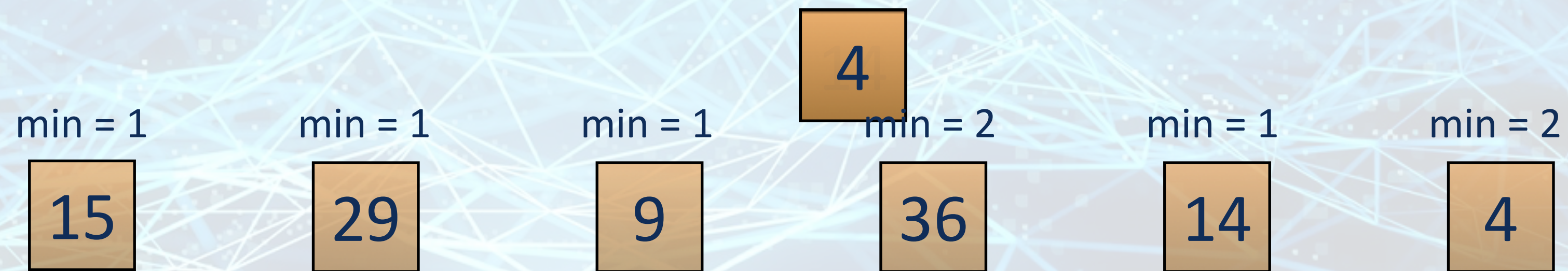
➤ **For each item  $v$**

➤  $C[h(v)] ++$

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

4 14 36 9 29 4 36 15

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



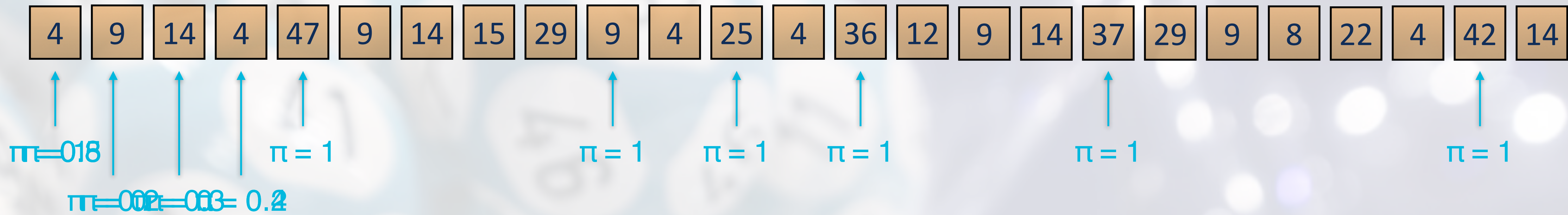


## ➤ Sampling in real-time data

- 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

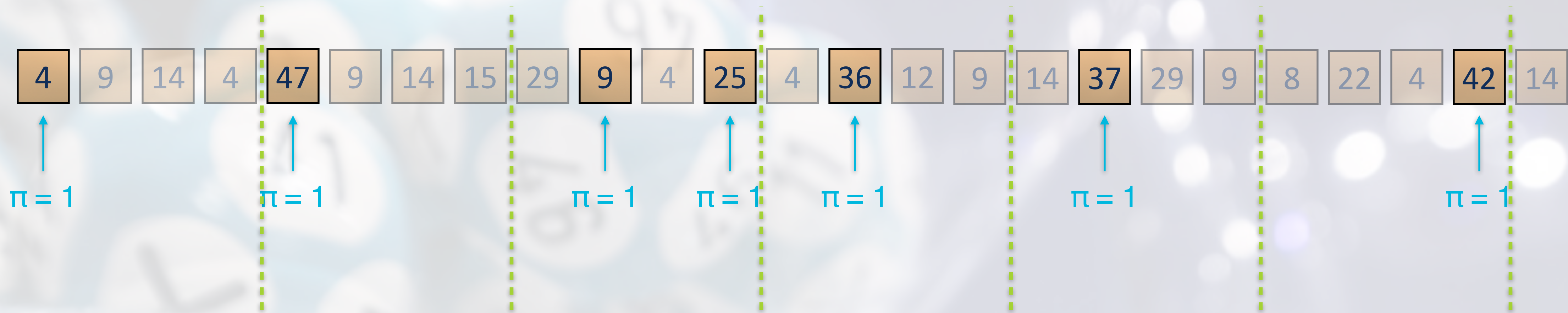


$$(\tilde{\pi}_i, \tilde{\pi}_j) = \begin{cases} (\min(1, \pi_i + \pi_j), \max(\pi_i + \pi_j - 1, 0)) \\ \quad \text{with probability } q \\ (\min(\pi_i + \pi_j, 1), \max(0, \pi_i + \pi_j - 1)) \\ \quad \text{with probability } 1 - q, \end{cases}$$

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

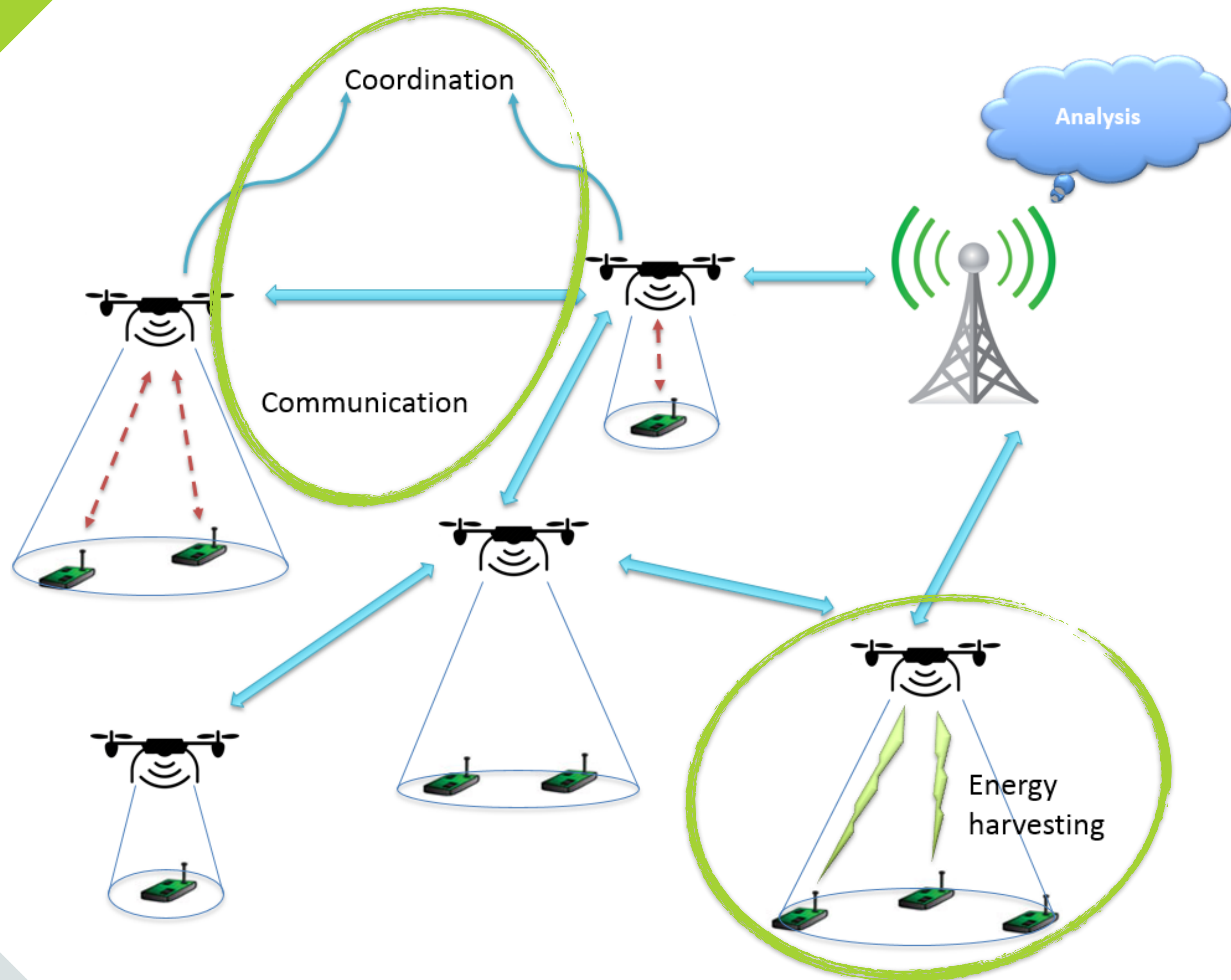
## ➤ Possible to generalize the pivotal sampling

- 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

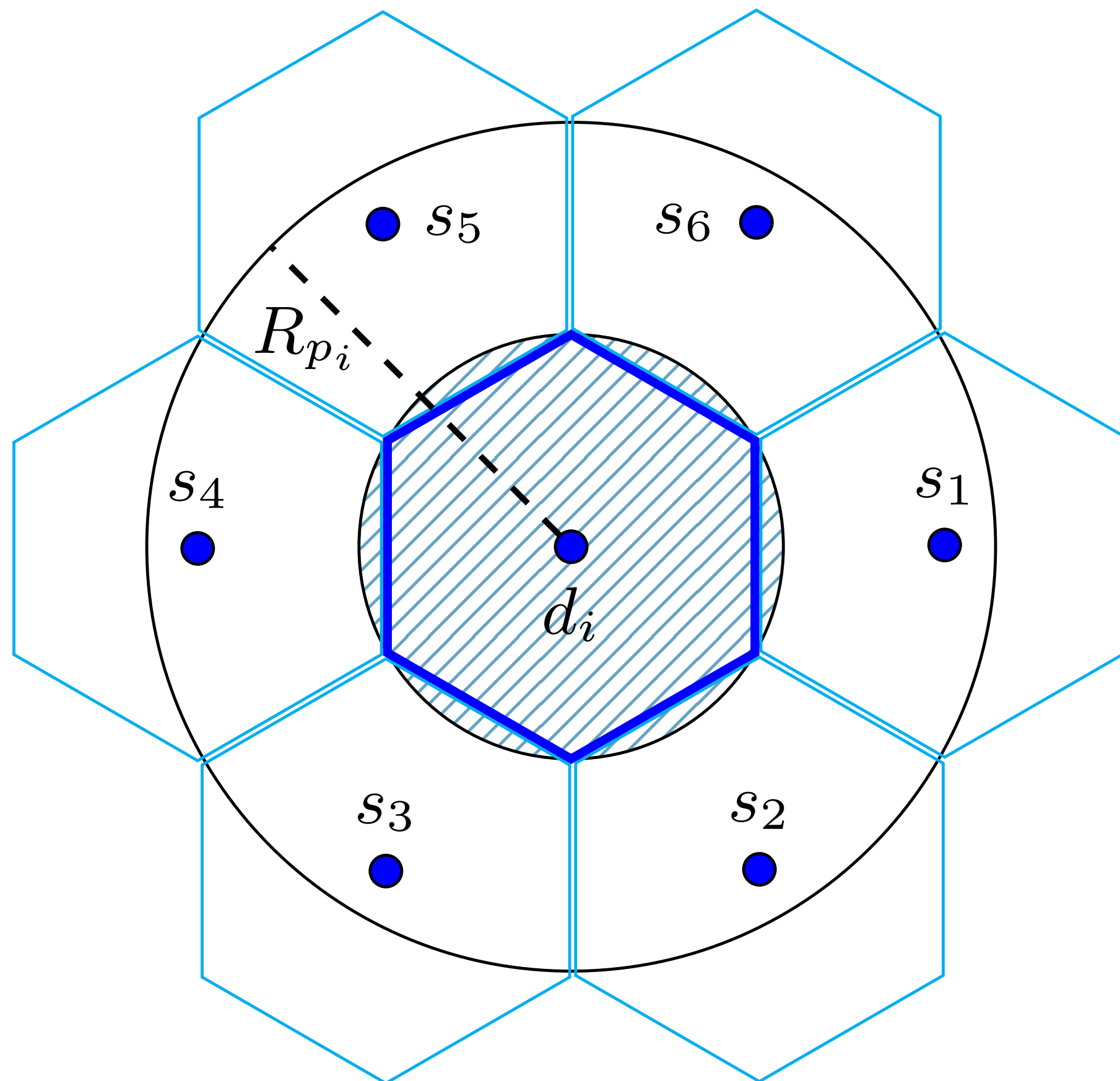
➤ Drones form a multi-hop aerial wireless path

➤ 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

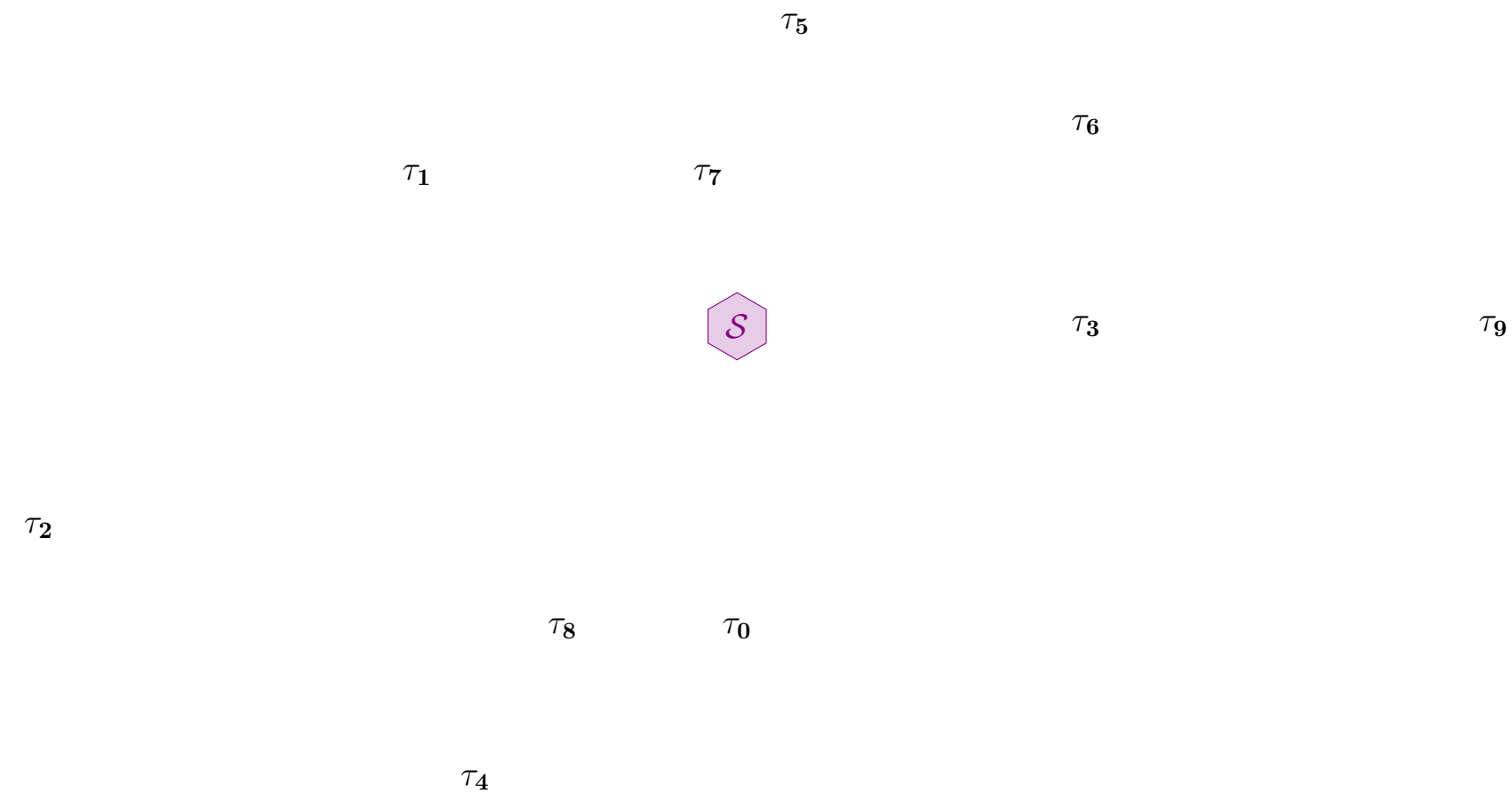




- Let  $D$  be a population of drones, identified by their id  $d_i, i \in \{1, \dots, |D|\}$
- Let  $p_i = (x_i, y_i, z_i)$  be the position of  $d_i$
- The sink  $S$  is located at  $p_s = (x_s, y_s, z_s)$
- Each drone  $d_i$  is equipped with an omnidirectional antenna. It is able to communicate with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

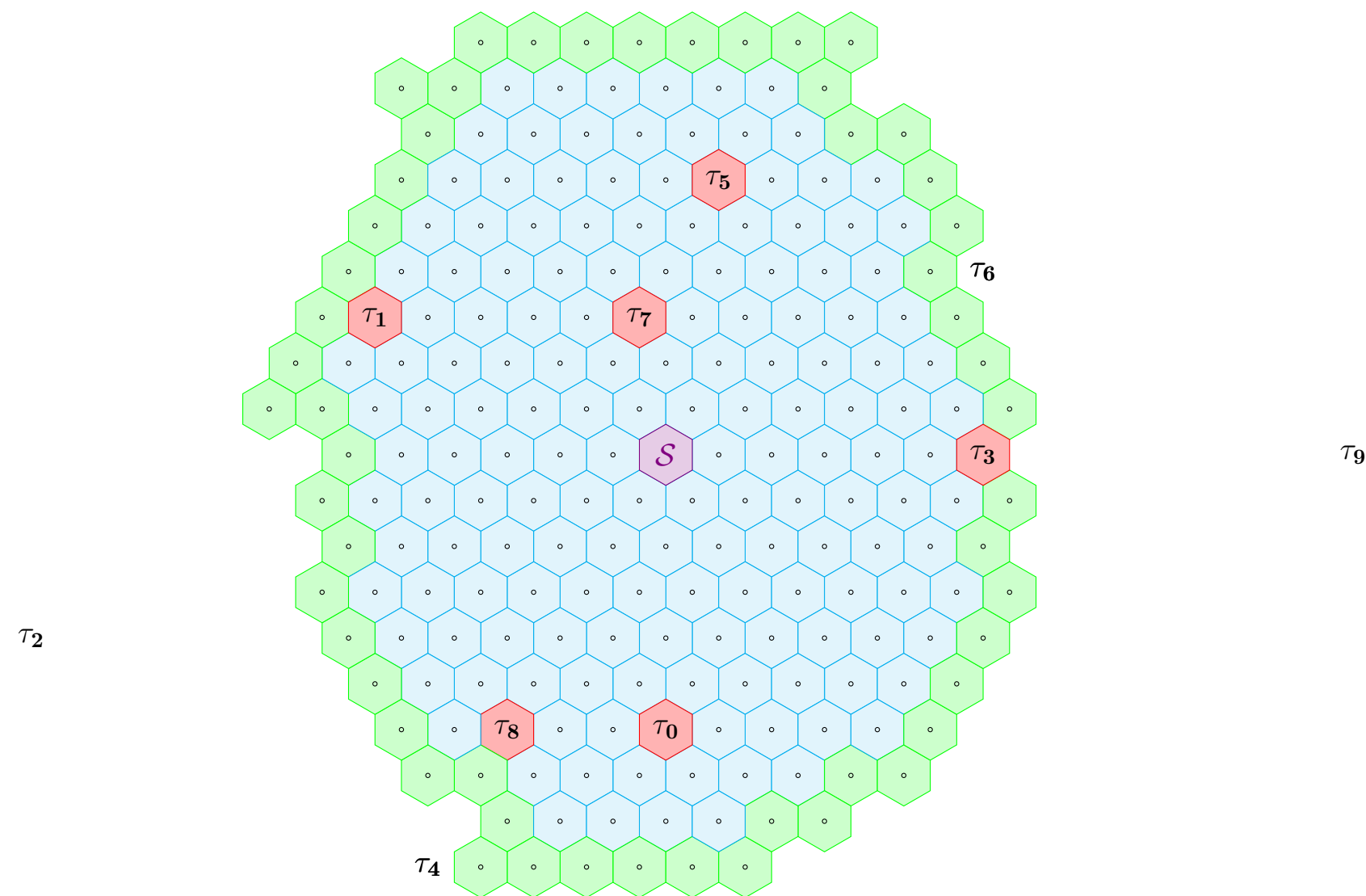
- All the  $n$  drones start at position  $p_s$
- Each drone runs independently the algorithm following an alternating of 3 phases
  - Expansion phase
  - Spanning phase
  - Balancing phase
- Each drone can take 3 possible states
  - Irremovable
  - Border
  - Free



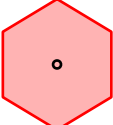
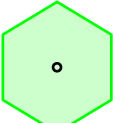
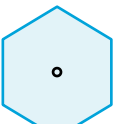


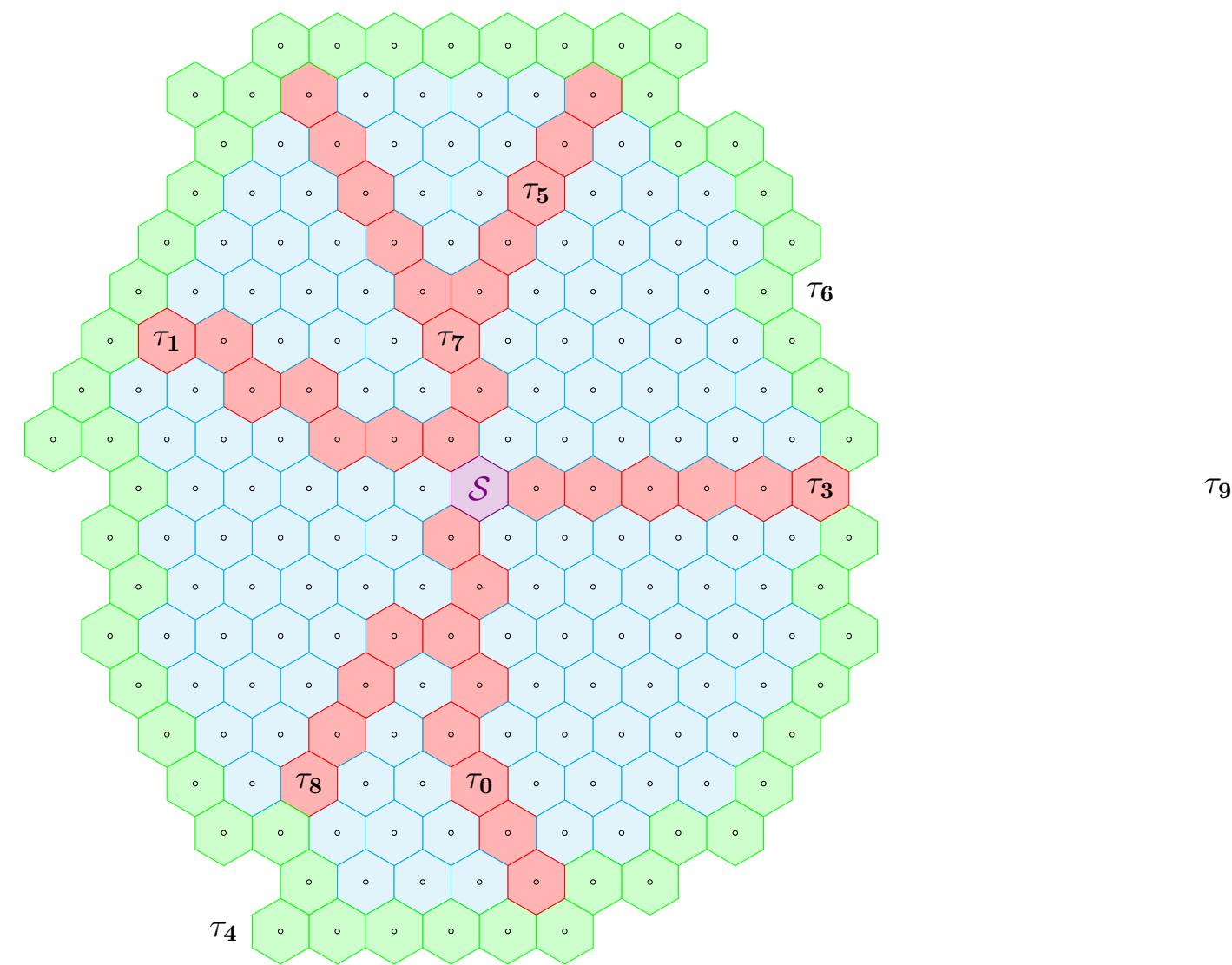
- Round 0 - Initialization
- All drones are located at S
- 10 targets to discover

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



## ➤ Key

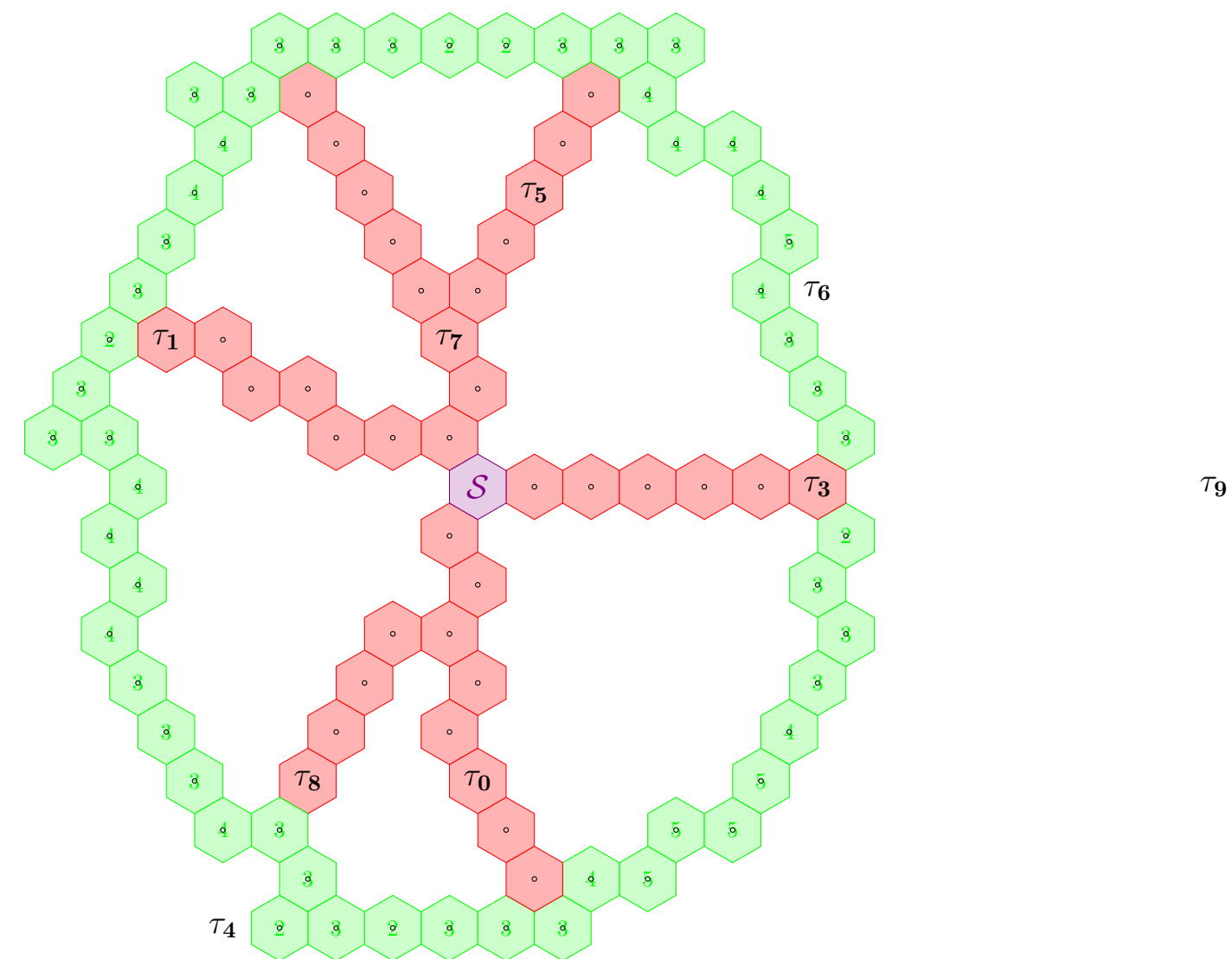
-  Irremovable
-  Border
-  Free



- **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

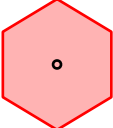
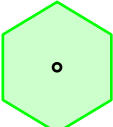
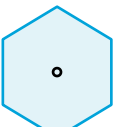
### ➤ All free drones have moved to the border

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

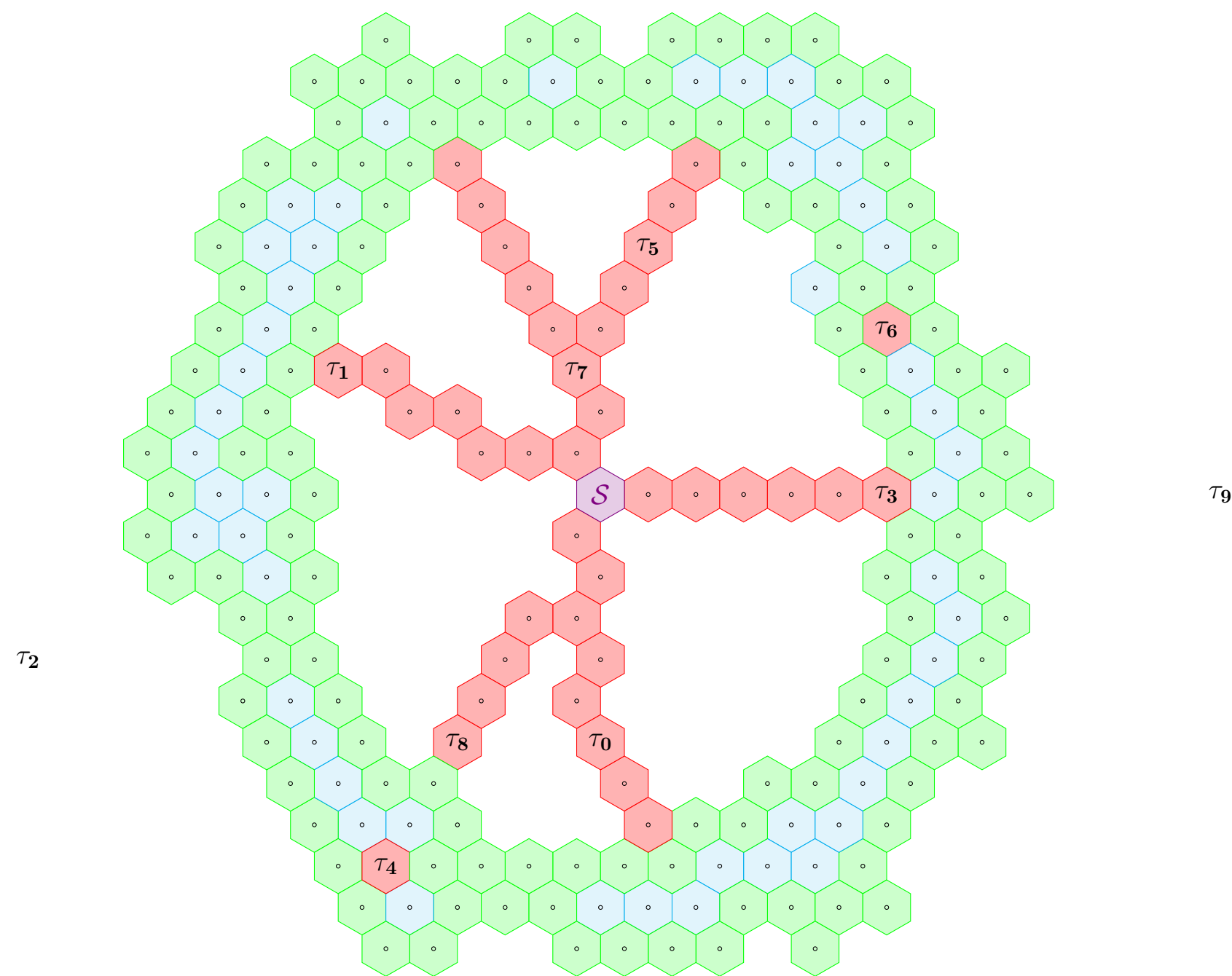
### ➤ Connectivity is guaranteed

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

### ➤ Key

-  Irremovable
-  Border
-  Free

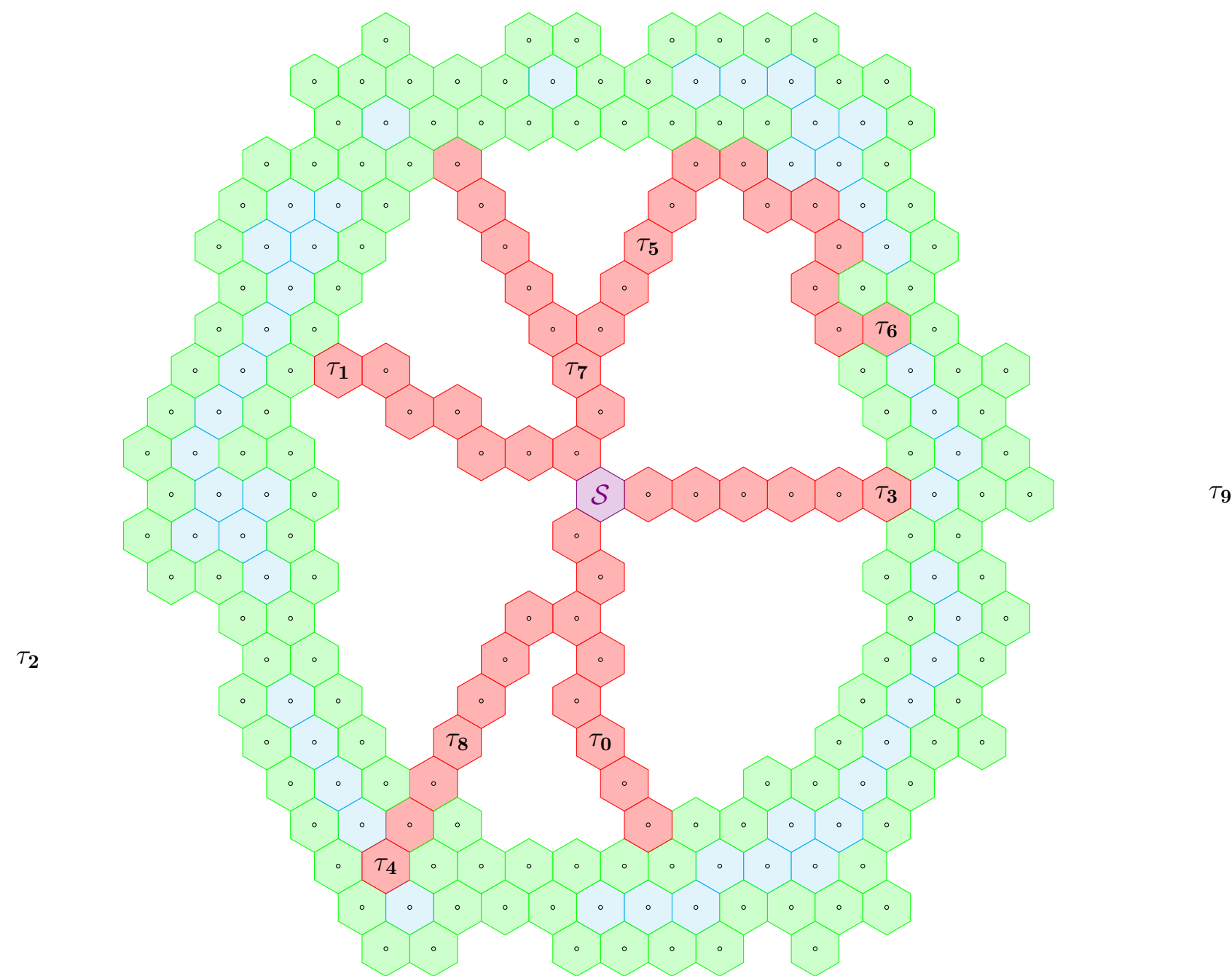




- **Round 2 - End of Expansion phase**
- **Any free drones have moved away from the former border**
  - A new border is self-defined by surrounding observation
- **Connectivity is still guaranteed**
  - From any drone using the previous spanning tree
  - Use of the right hand algorithm to find a path 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

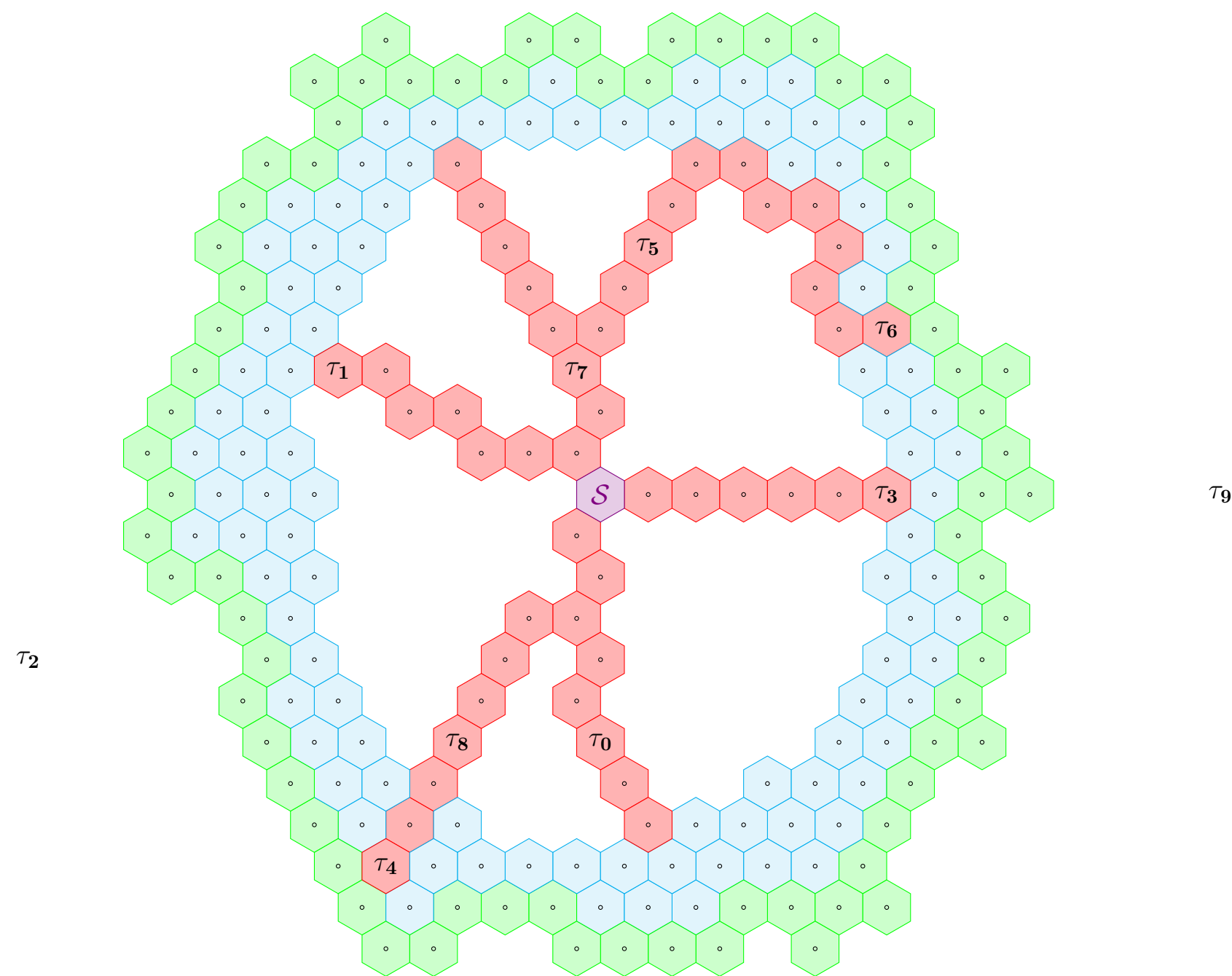
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### ➤ Key

◻ Irremovable

◻ Border

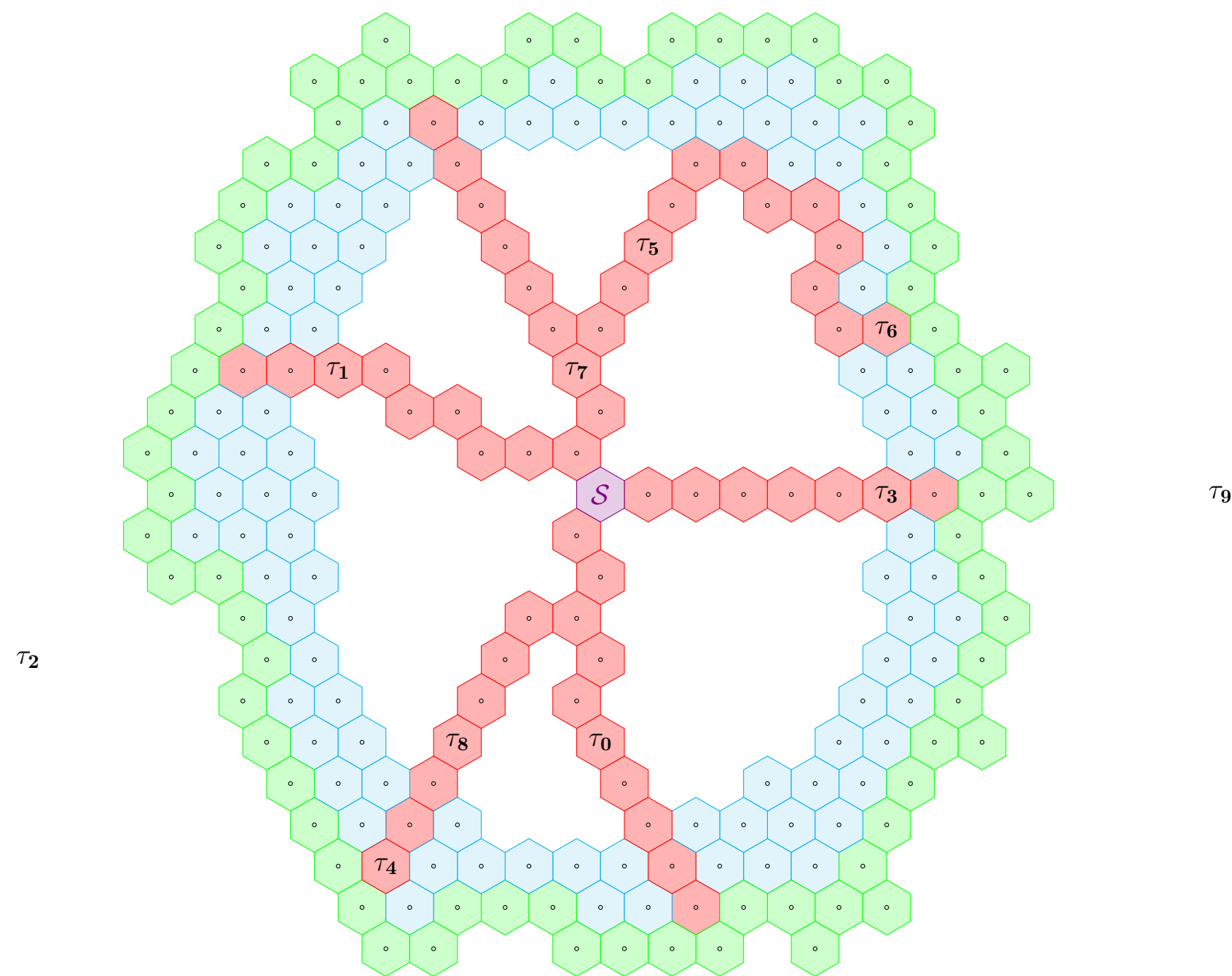
◻ Free



- **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**

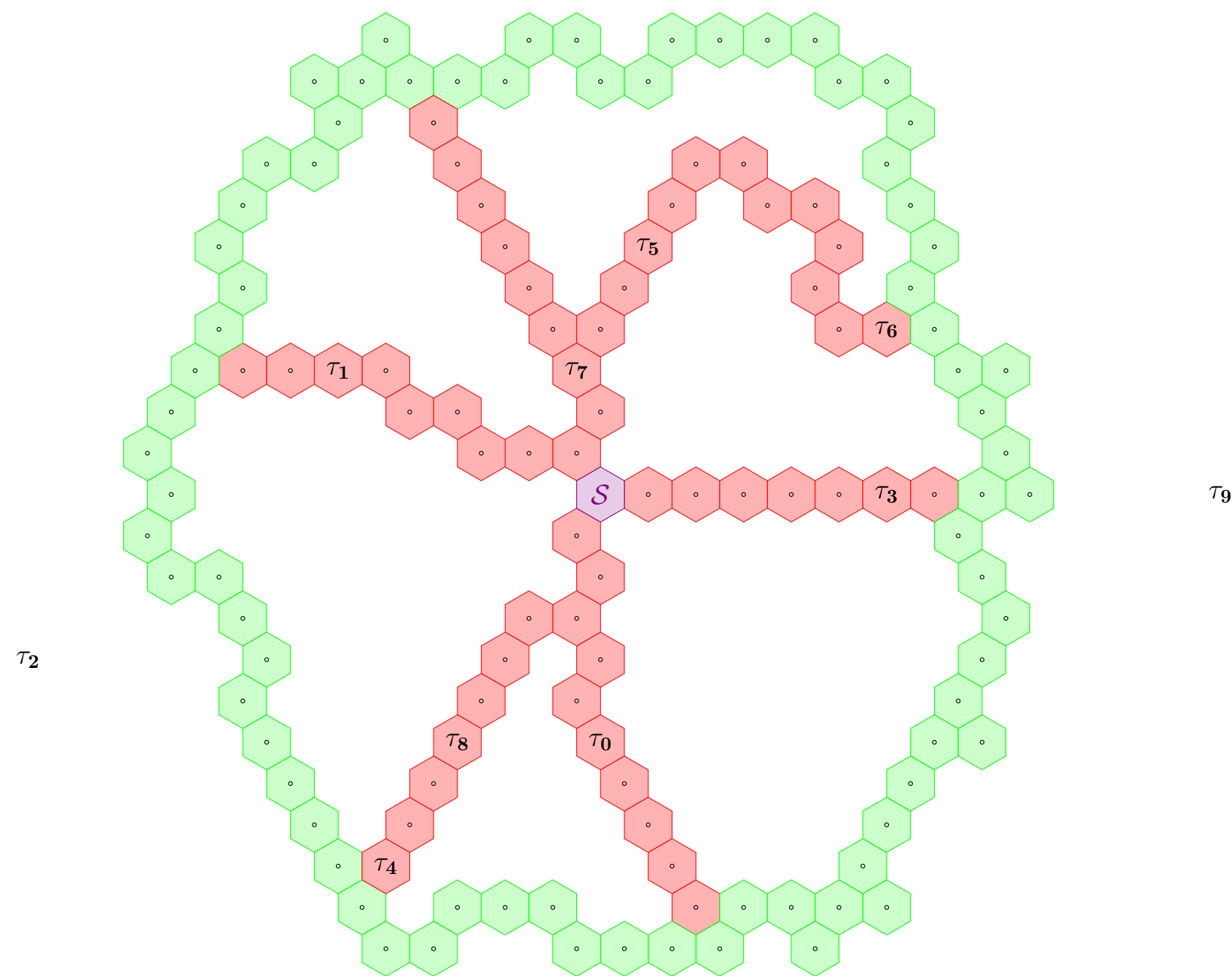
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➤ **Key**

◻ 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

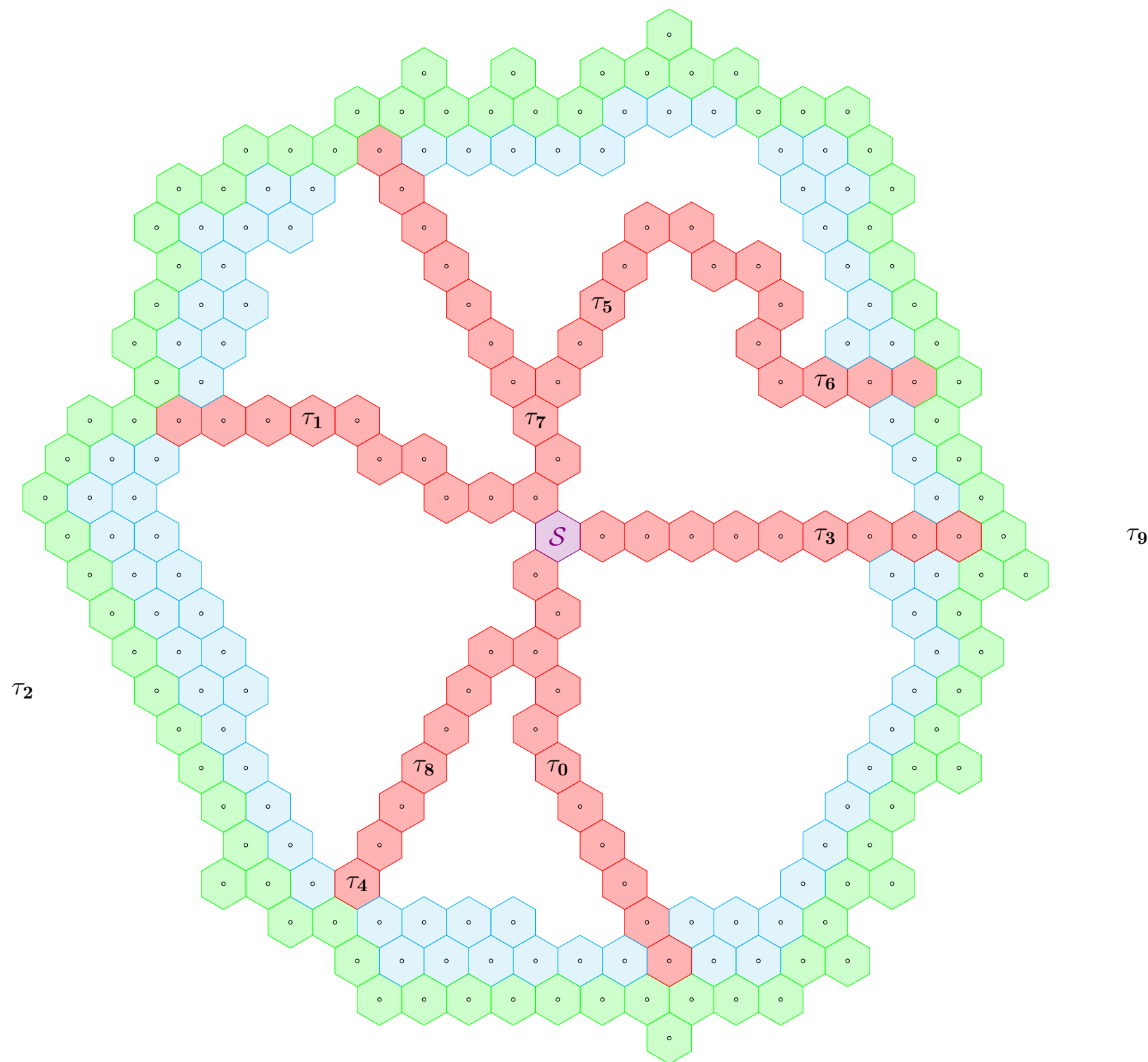
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### ➤ Key

 Irremovable

 Border

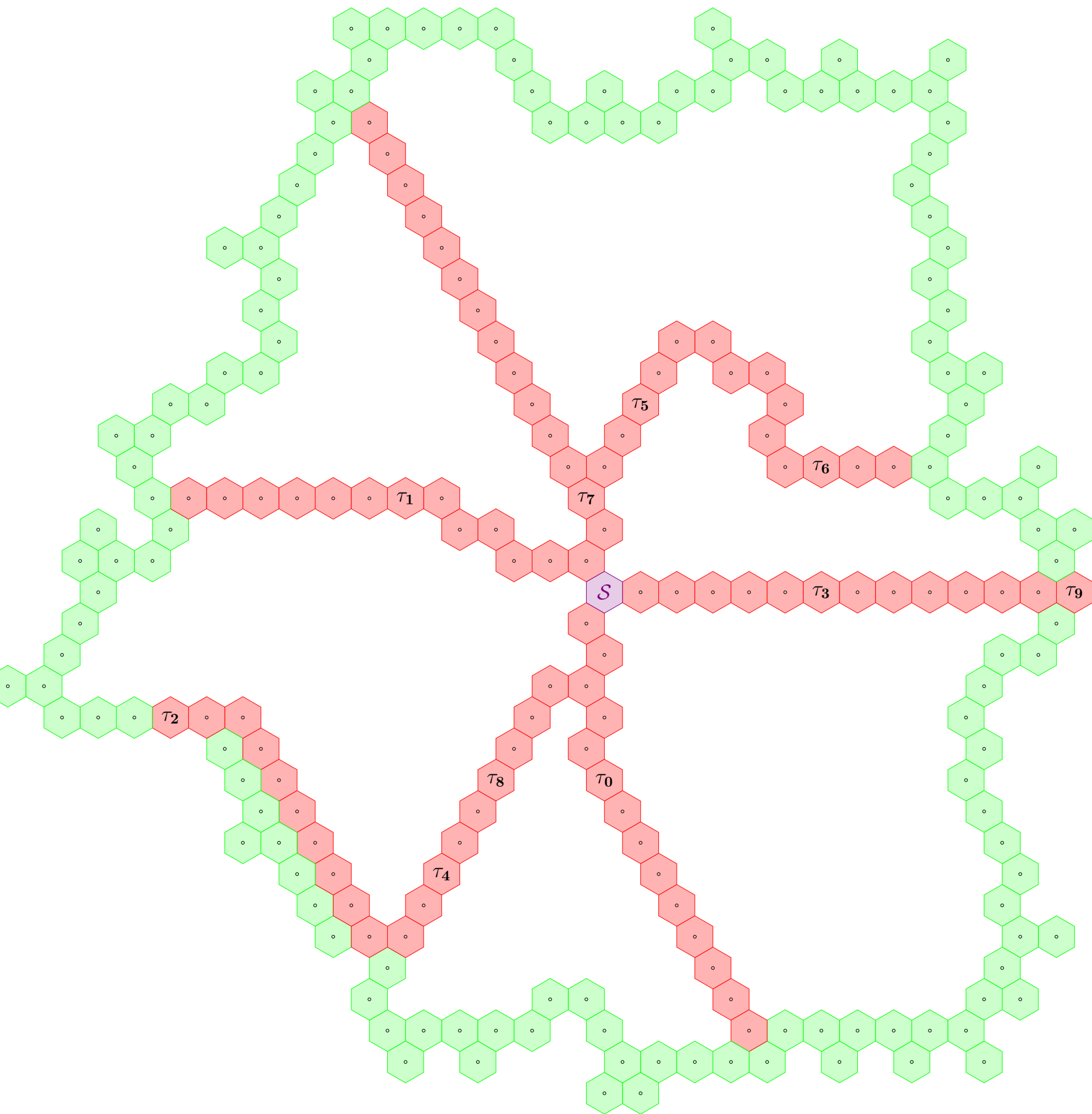
 Free



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

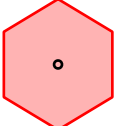
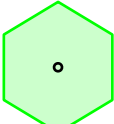
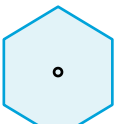
## ➤ Key

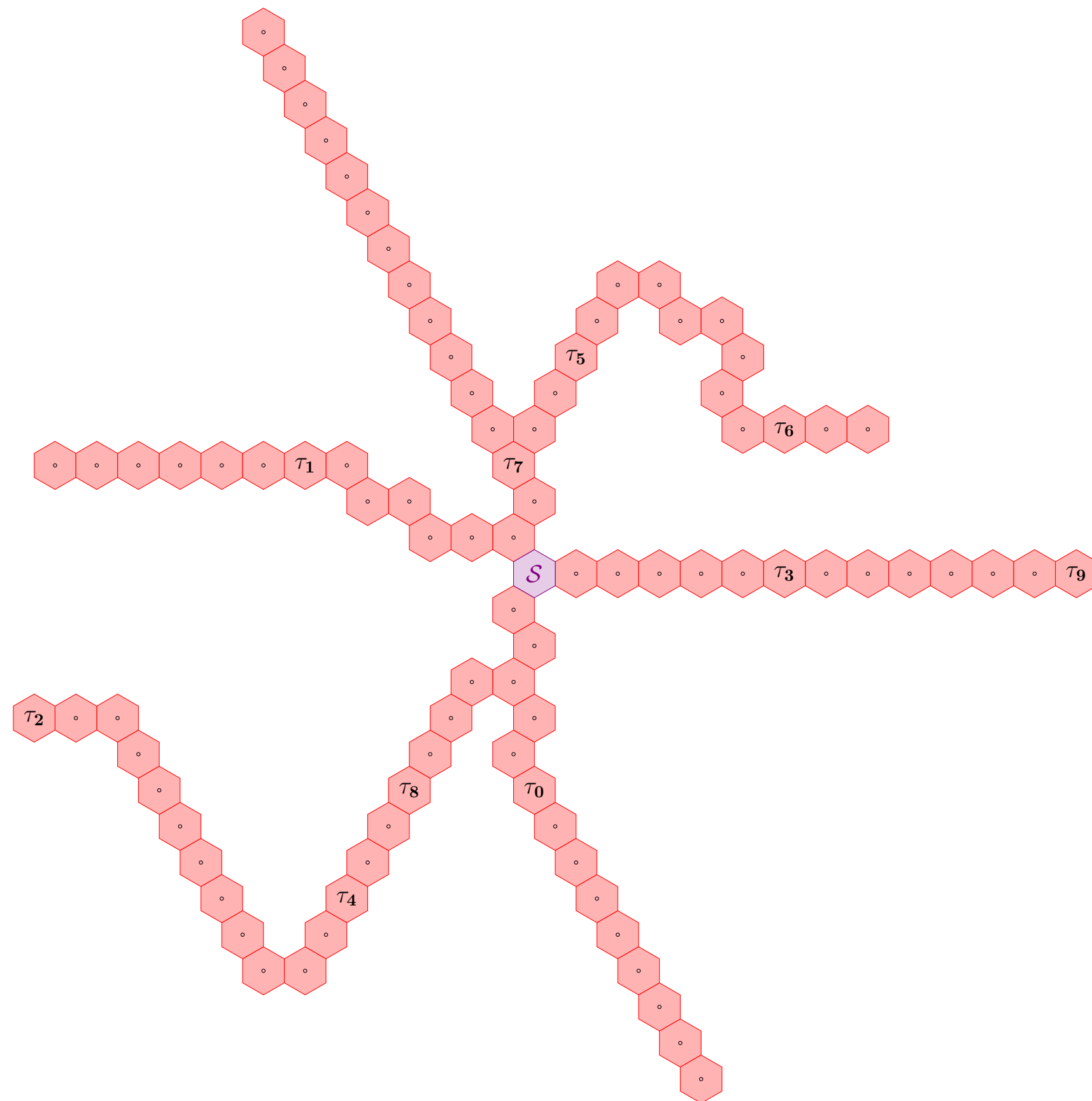
- ◻ Irremovable
- ◻ Border
- ◻ Free



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

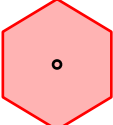
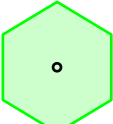
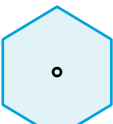
## ➡ Key

-  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

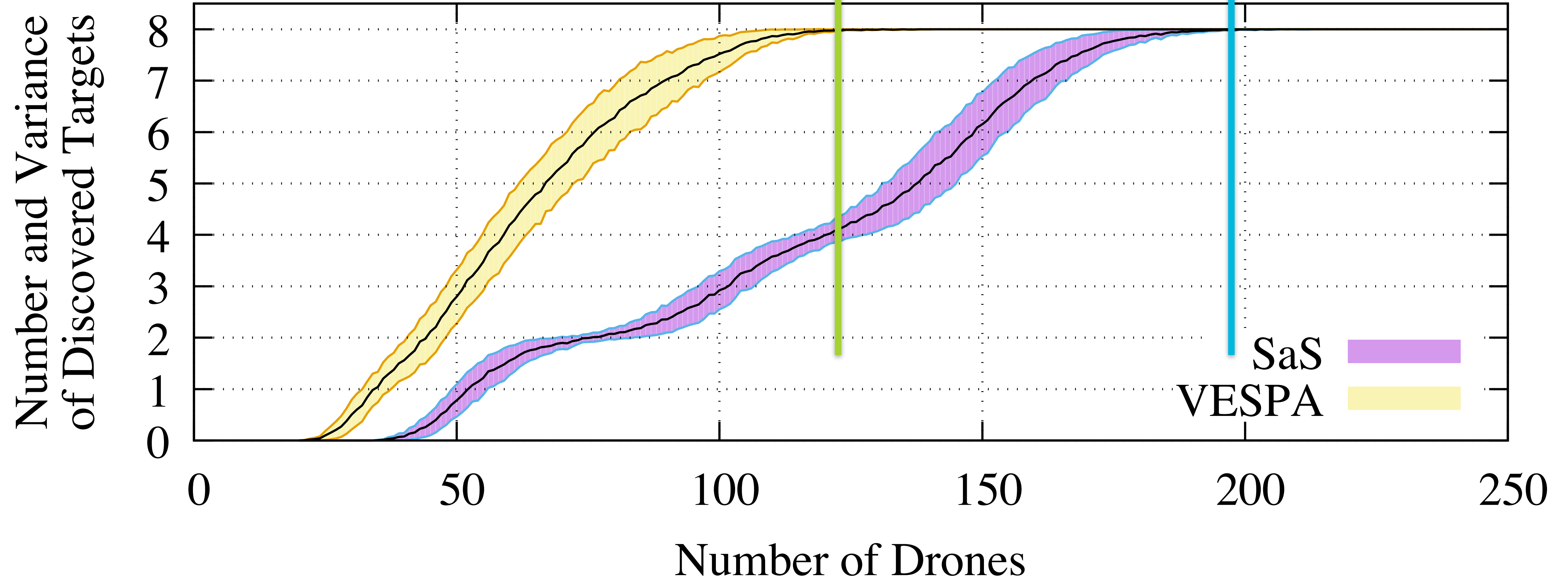
# PERFORMANCE EVALUATION

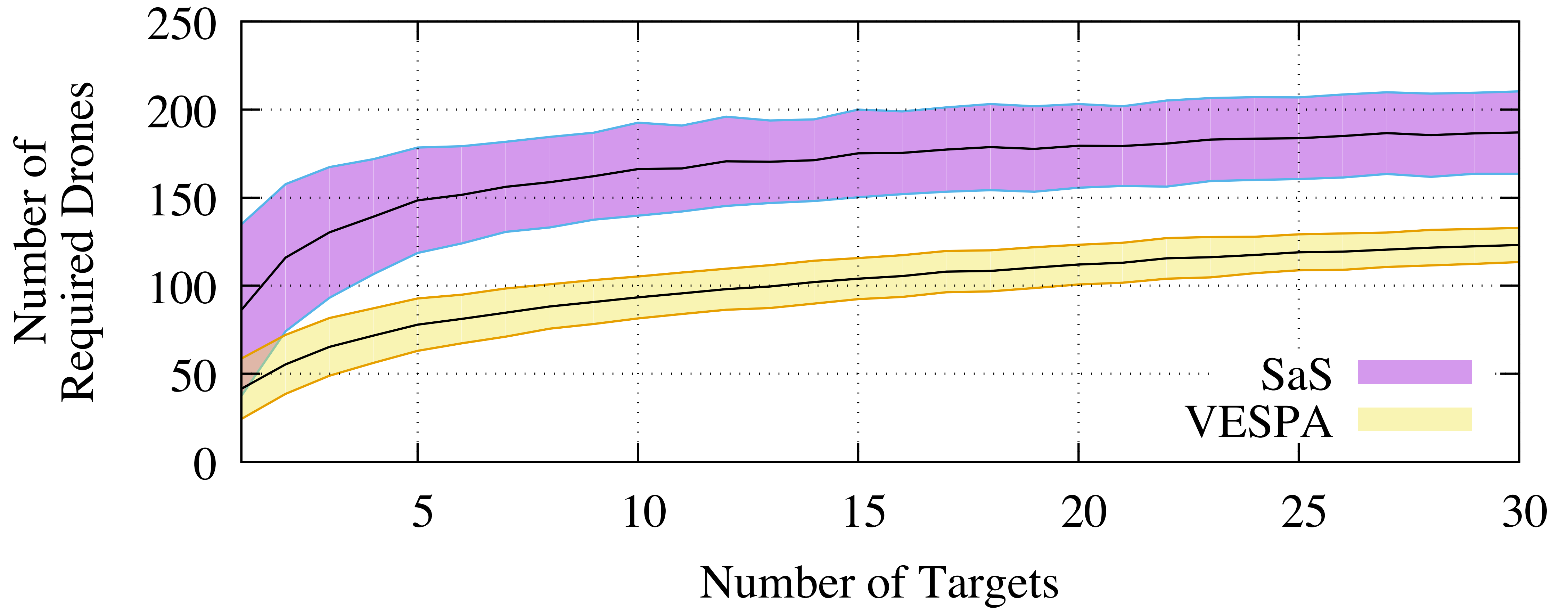
- **Randomly deploy targets around the sink**
  - Unknown coordinates to the drones and the sink
- **Number of targets vary from 1 to 30**
- **Number of drones from 10 to 250**
- **Communication range  $R_{p_i}$  sets to 20m**
  
- **Comparizon with the closest related work [1]**

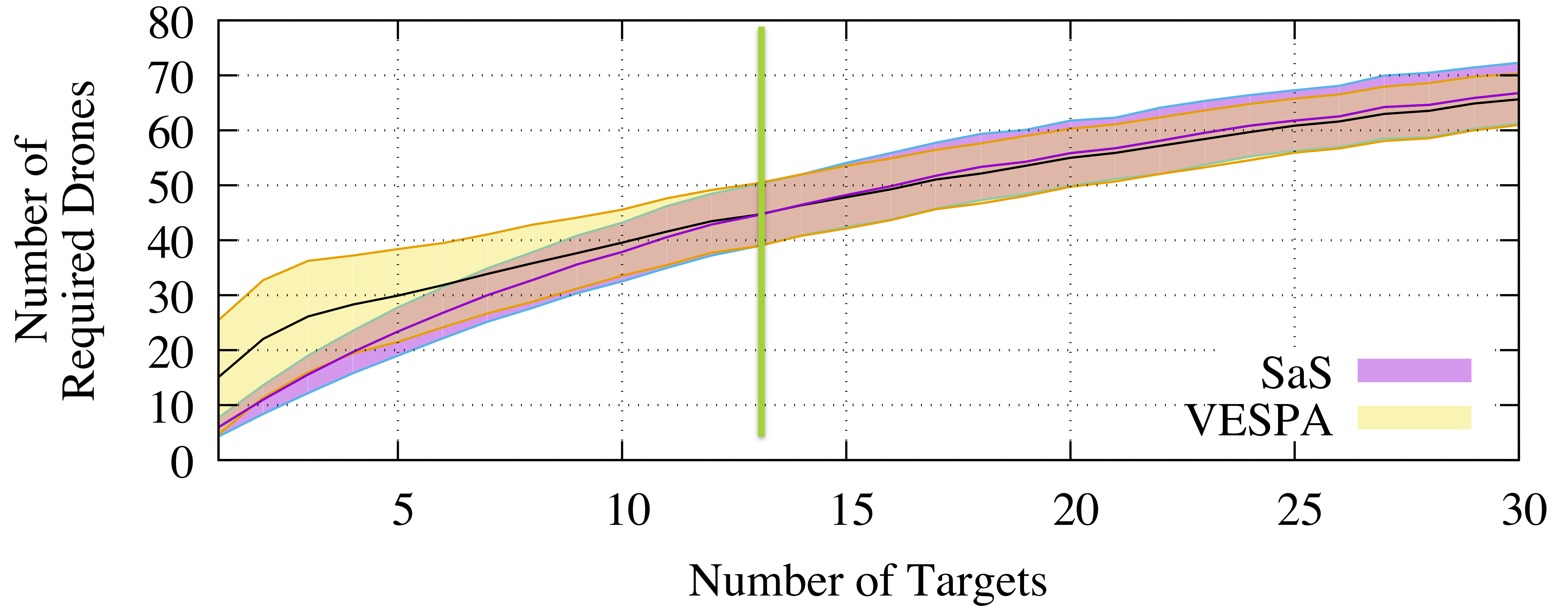
[1] T. Razafindralambo, M.Erdelj, D.Zorbas, and E.Natalizio, “*Spread and shrink: Point of interest discovery and coverage with mobile wireless sensors*”, Journal of Parallel and Distributed Computing, vol. 102, pp. 16 – 27, 2017.

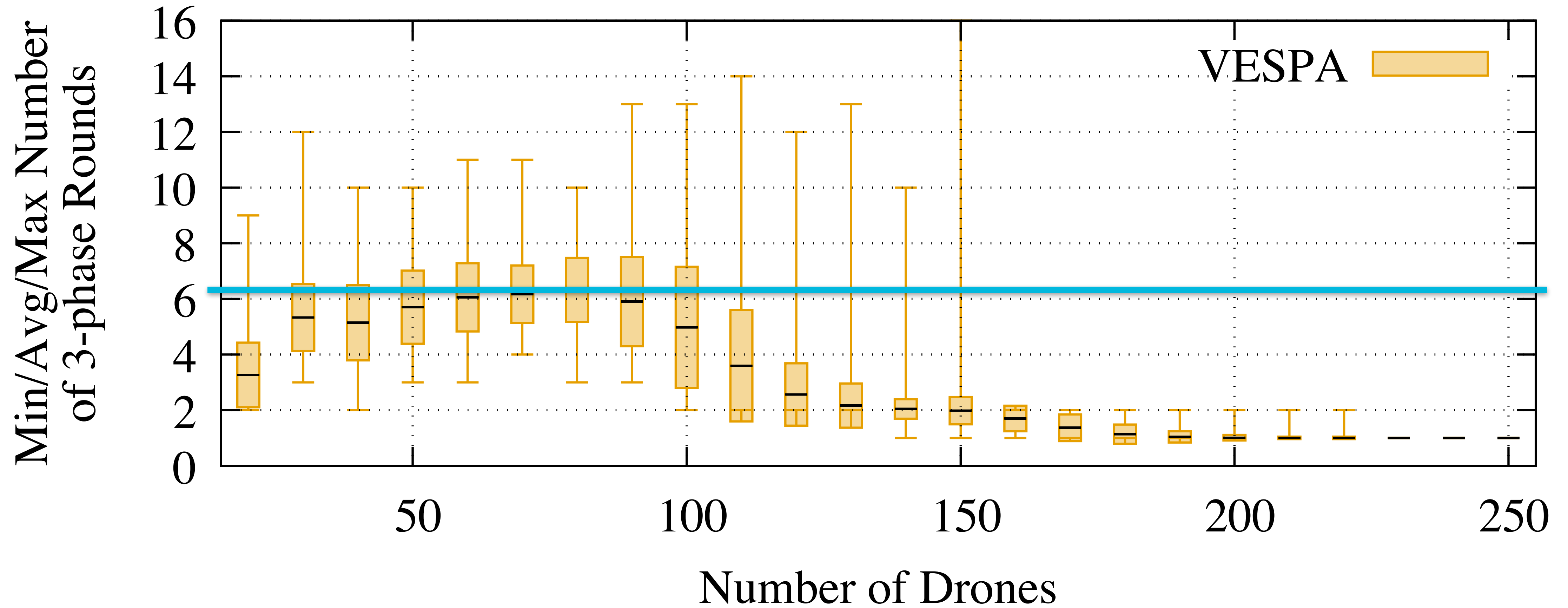
# AVERAGE NUMBER OF DISCOVERED TARGETS

— 8 TARGETS LOCATED IN SQUARE AROUND THE SINK









# 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

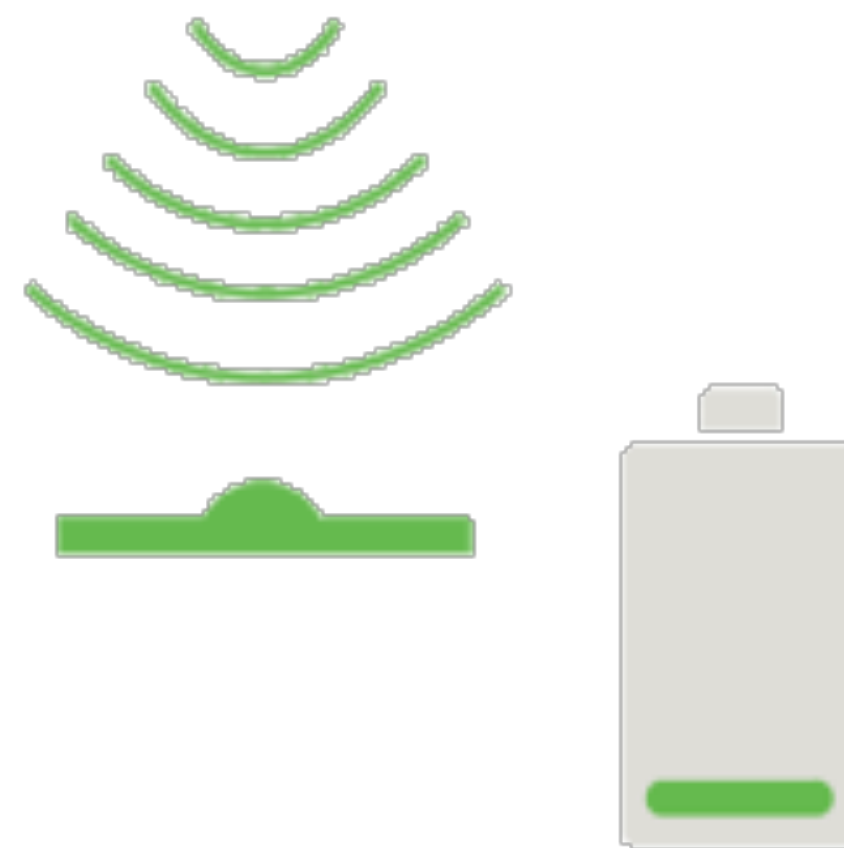


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École Mines-Télécom



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

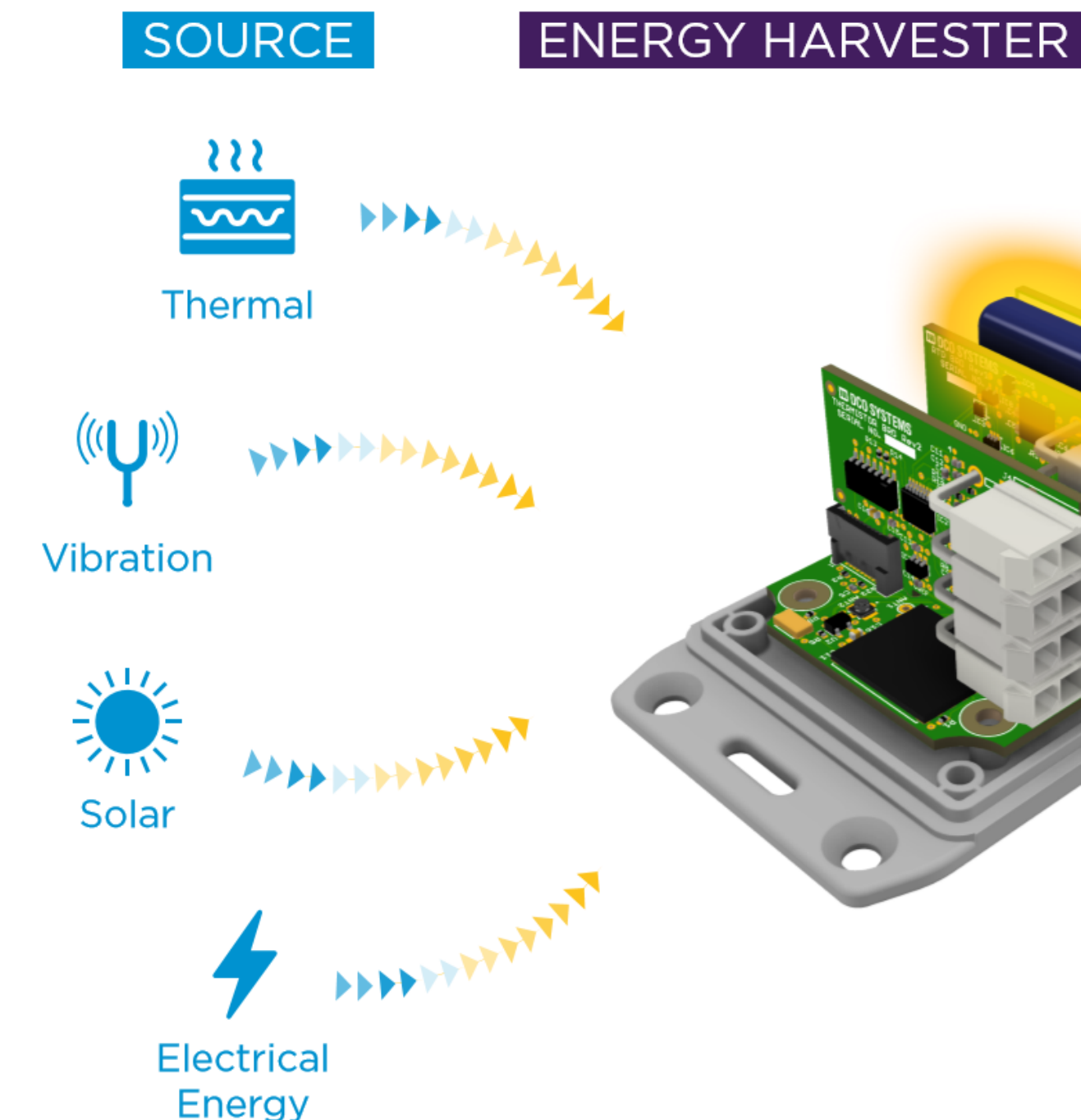
- Fast expansion
- Large set of usecases
  - industry 4.0
  - military
  - home automation
  - ecology
  - precision agriculture
  - disaster management
  - etc.

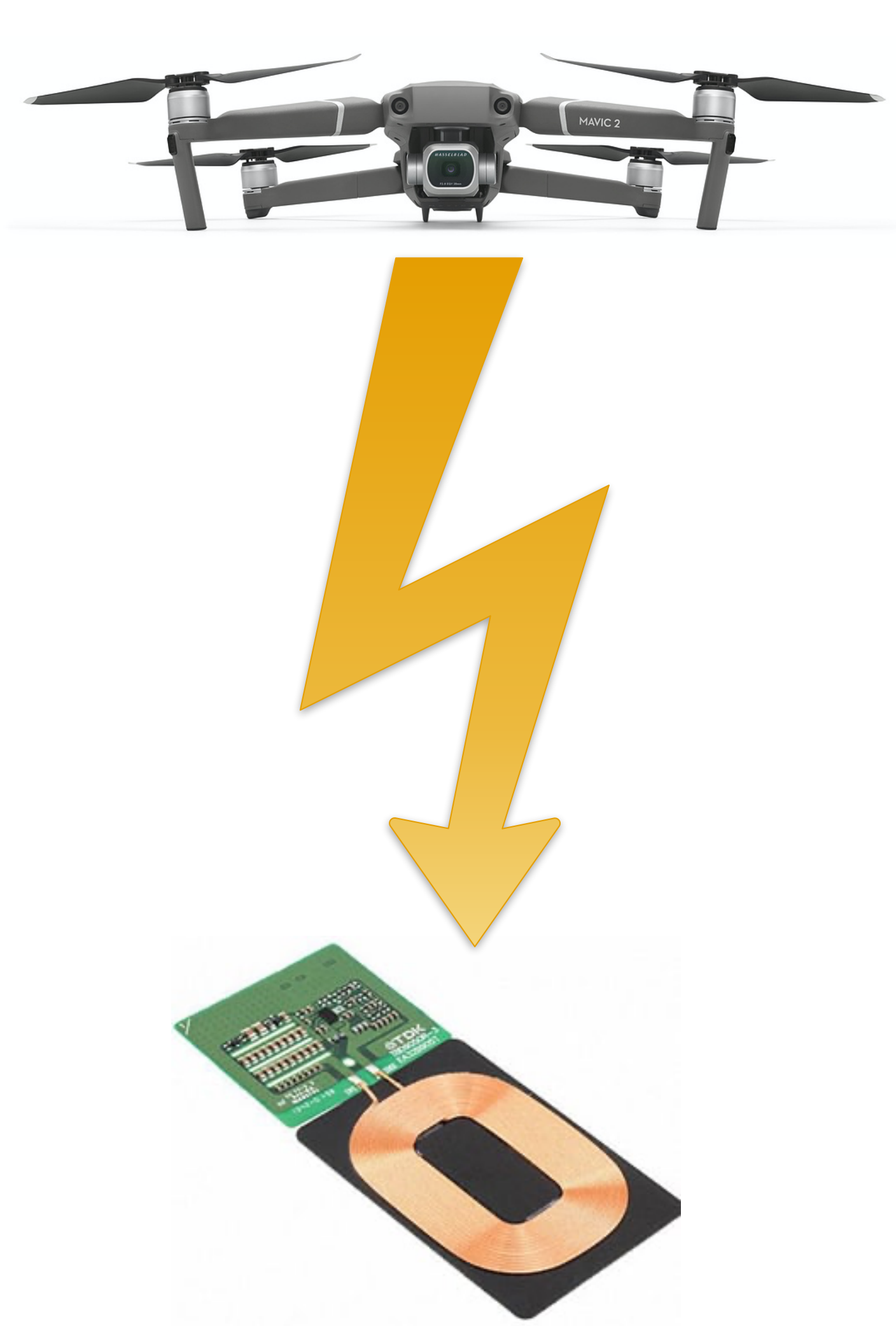
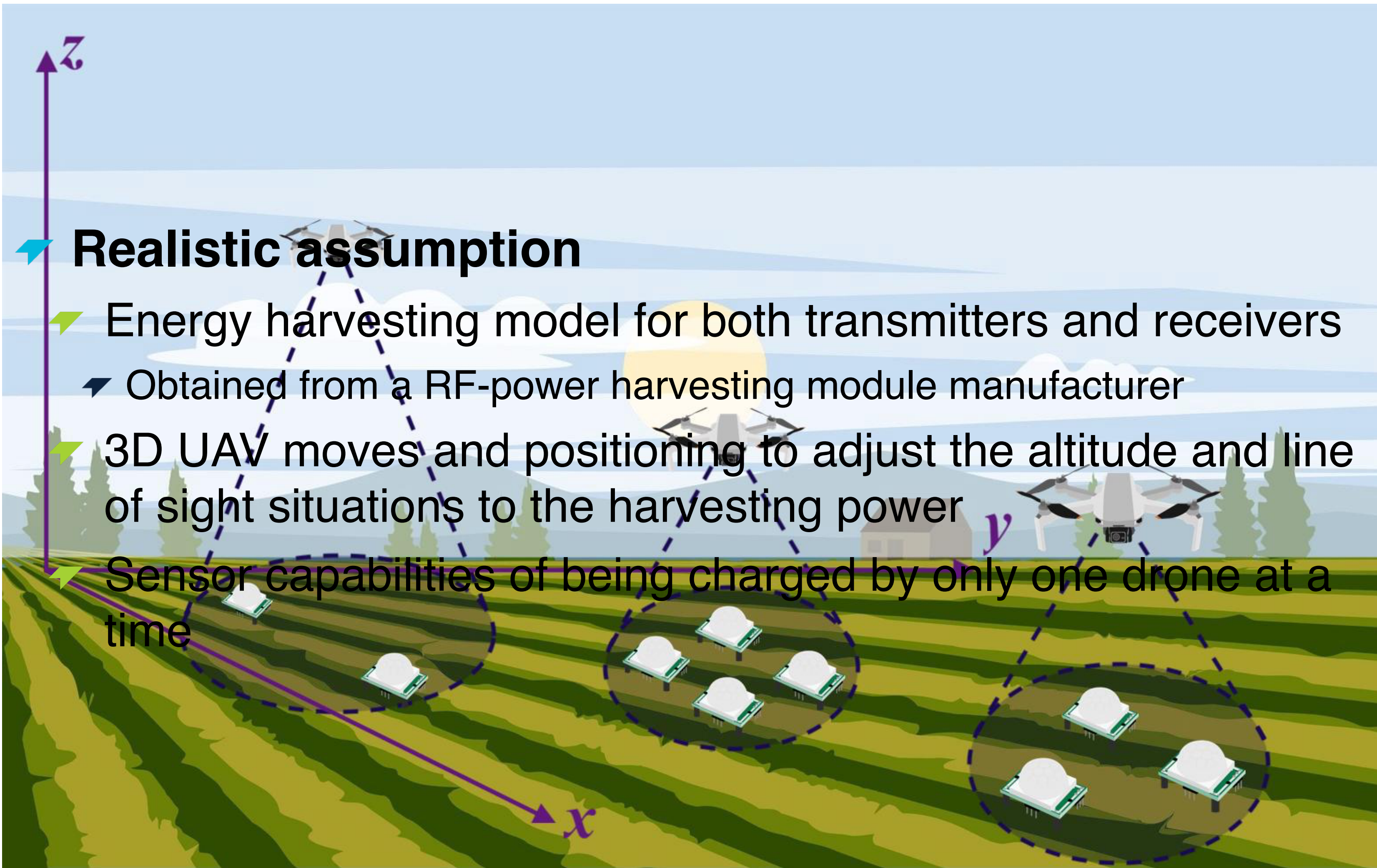
## ➤ Require the implementation of sensor systems over long periods of time

- 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

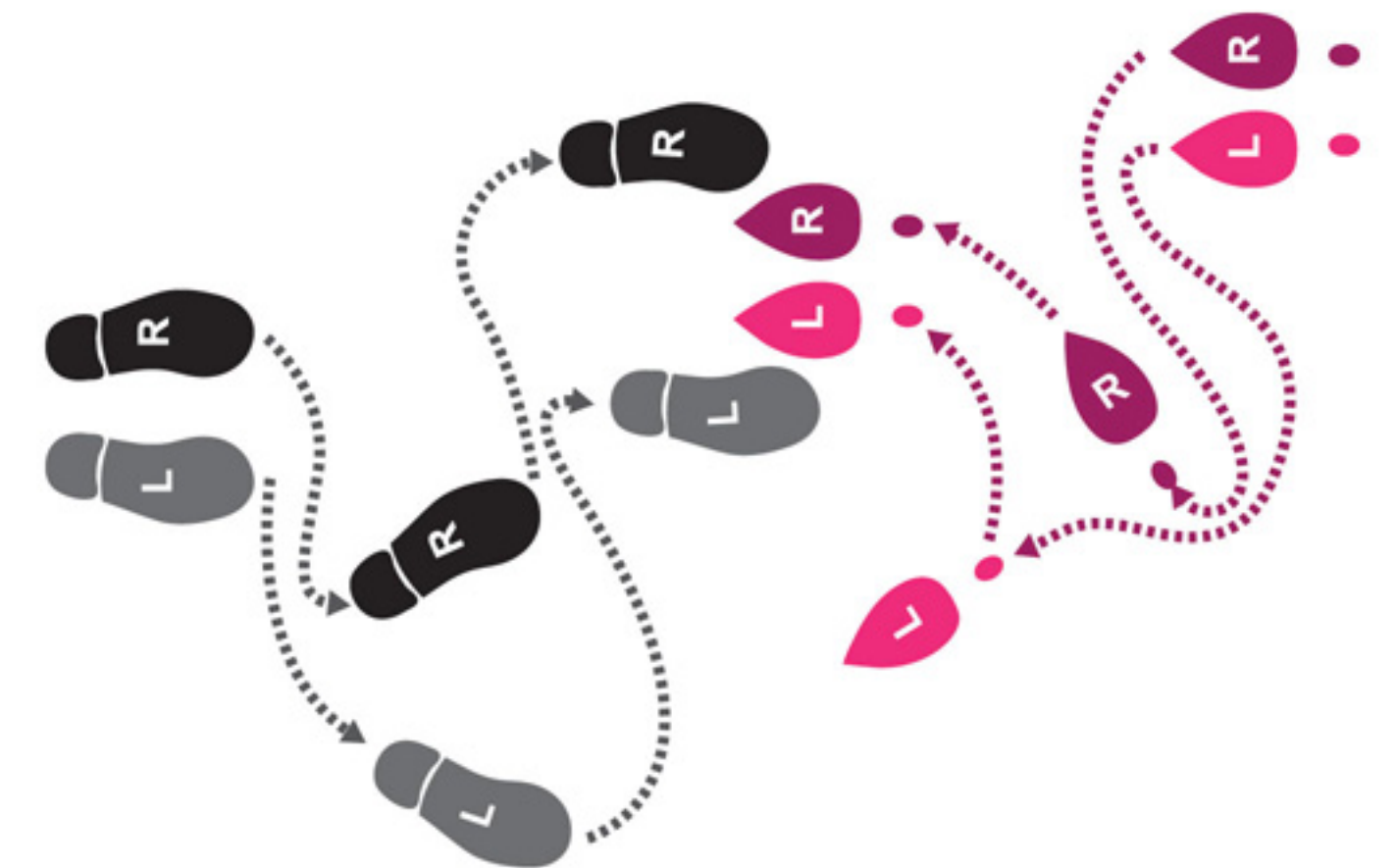
### ➤ **Adaptability and scalability**

- 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  $\sigma$   
-  $P_0$  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

## Objective:

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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  $\lambda_1$
- the worst number of positions  $\lambda_2$

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

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

# OPTIMAL POSITIONING : MILP APPROACH

Define 2 continuous variables modeling

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

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

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

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

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

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

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

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

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

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

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



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

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

- **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

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

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

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

# 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]

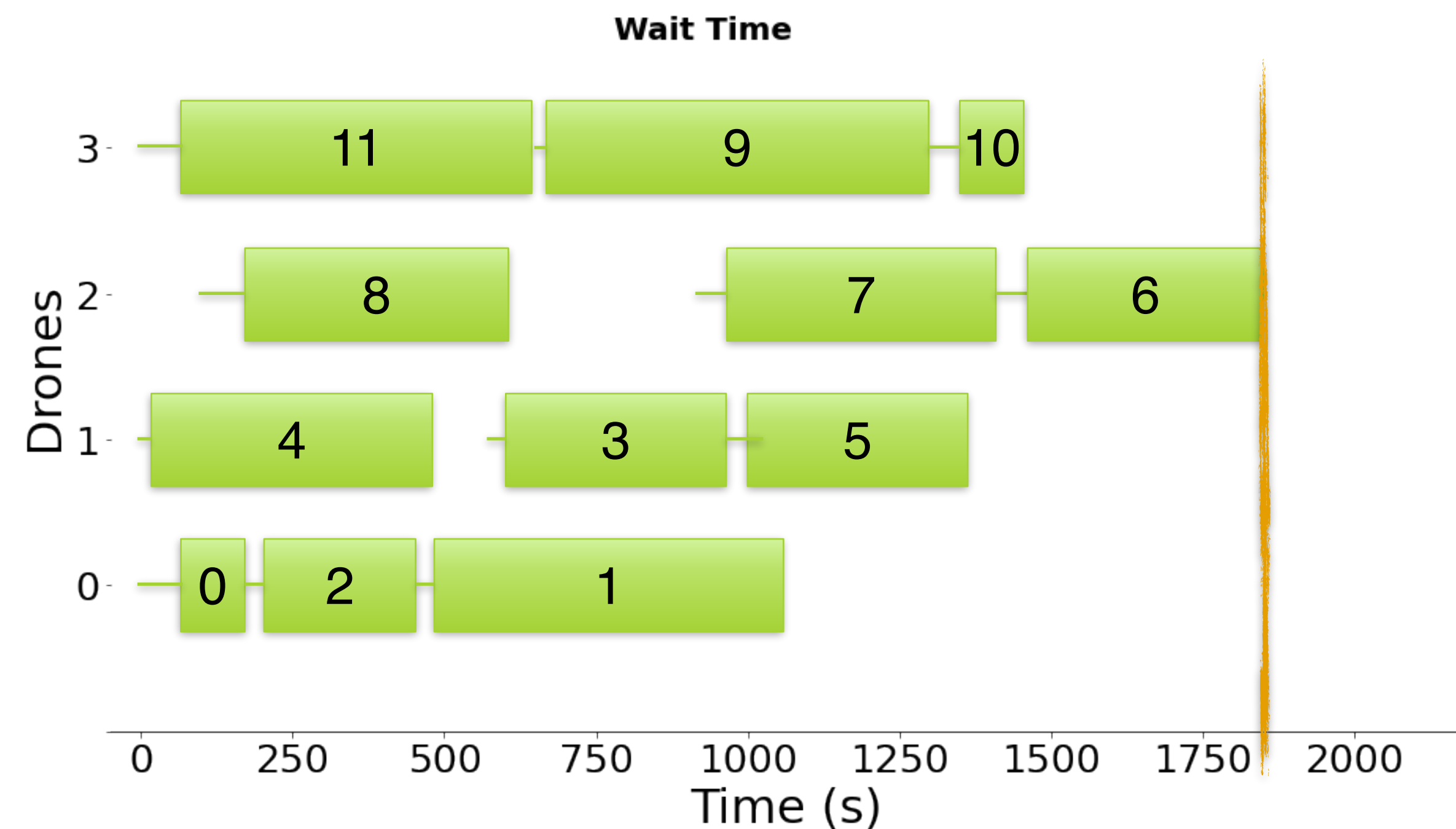
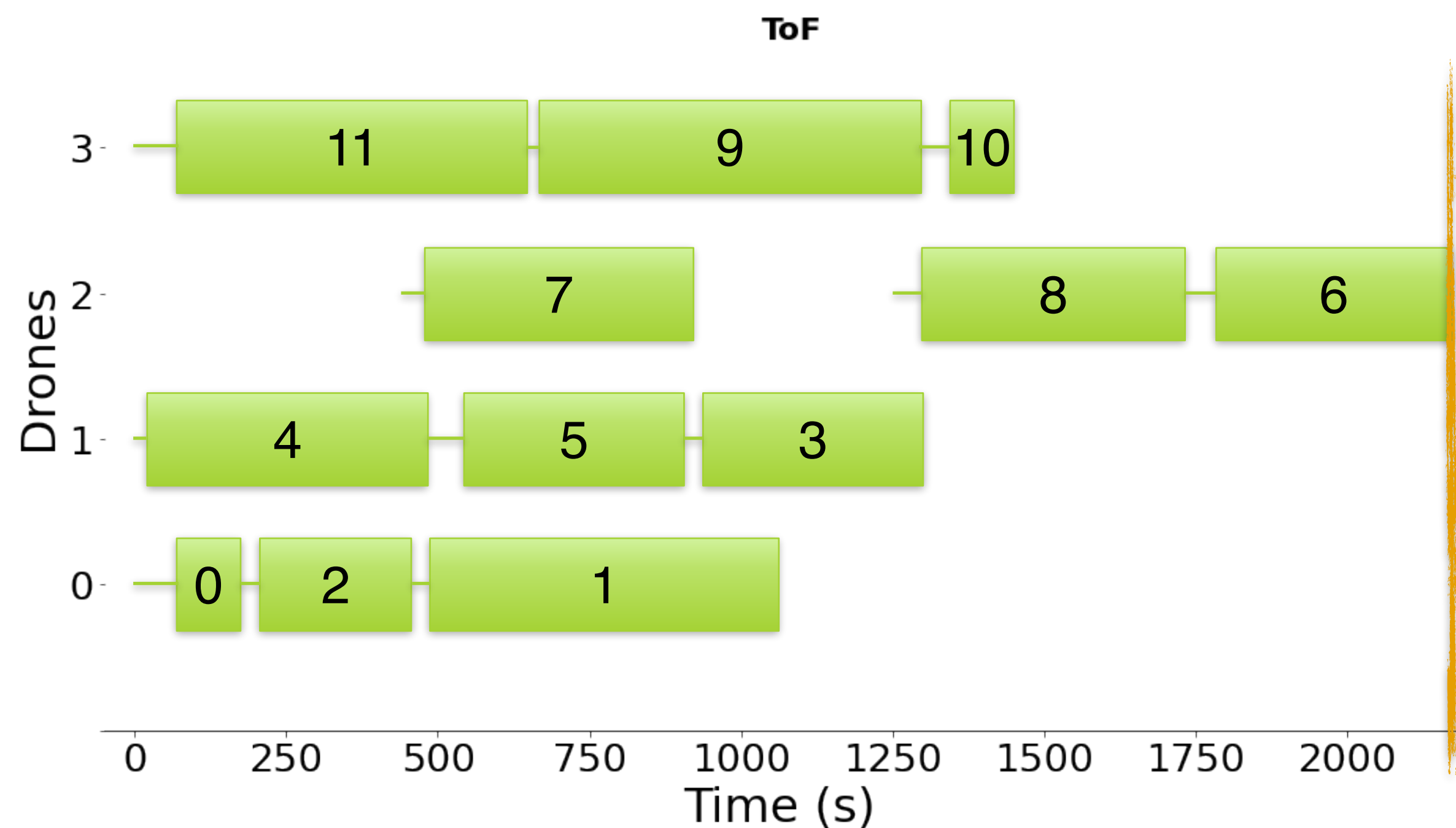
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## Tasks by drone

- d<sub>0</sub> = [0, 1, 2]
- d<sub>1</sub> = [3, 4, 5]
- d<sub>2</sub> = [6, 7, 8]
- d<sub>3</sub> = [9, 10, 11]

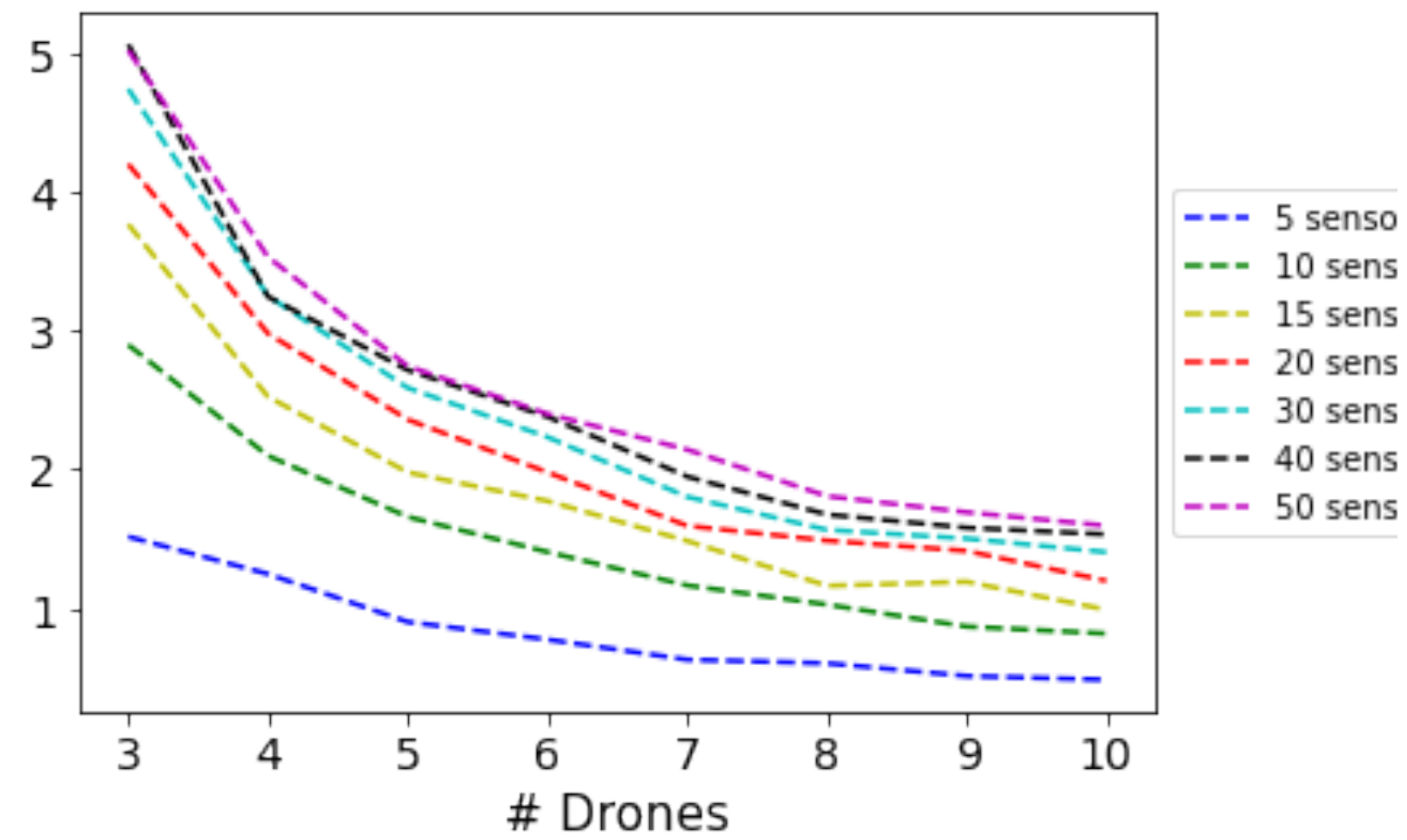
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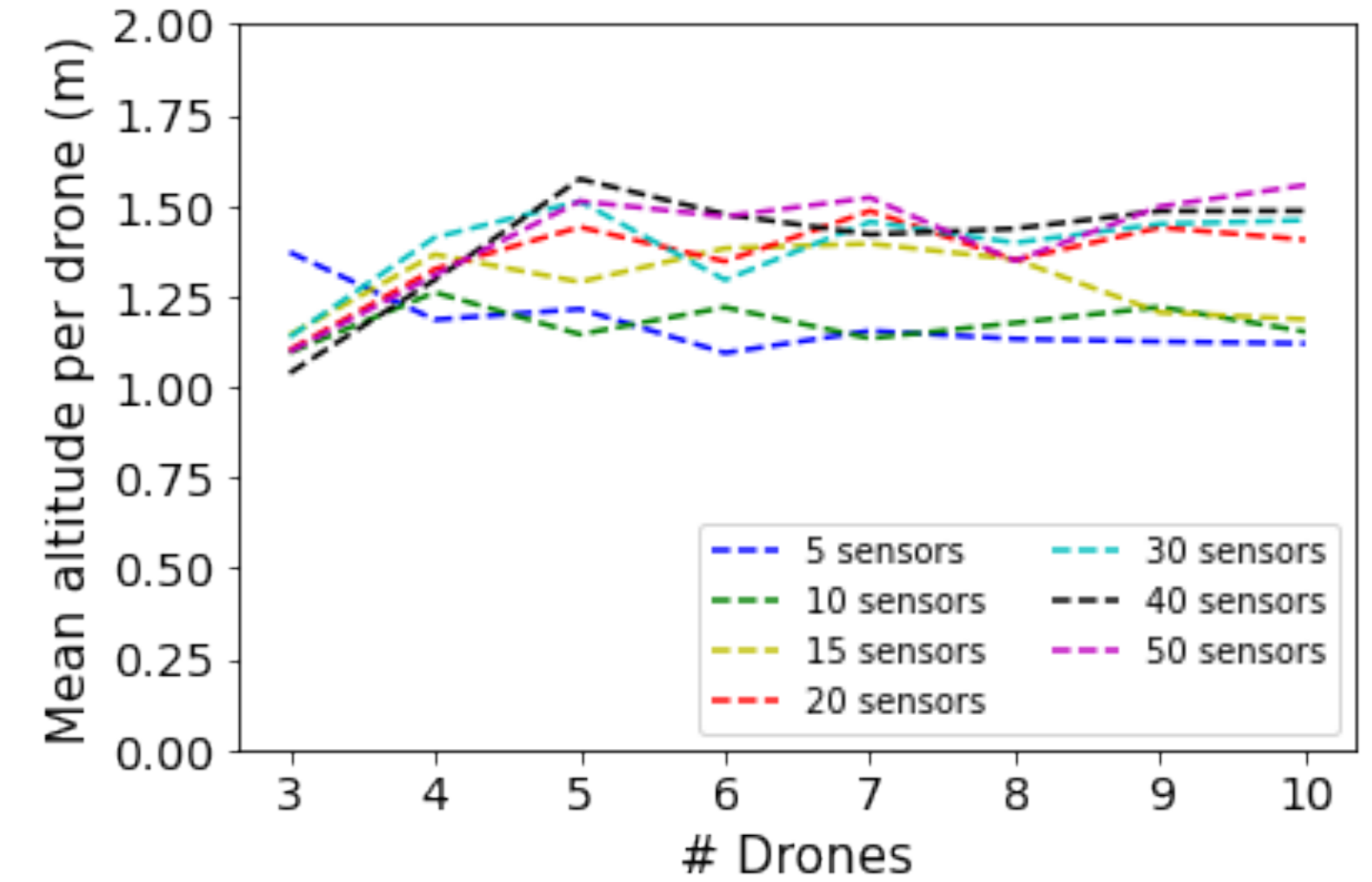


# PERFORMANCE EVALUATION MILP

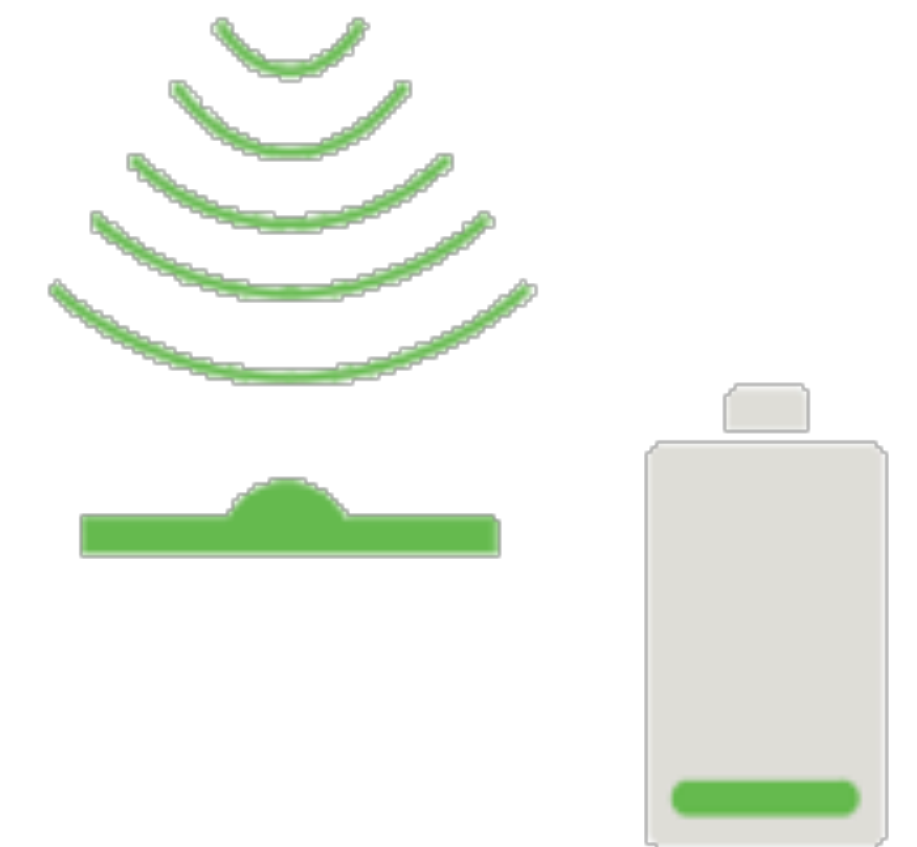
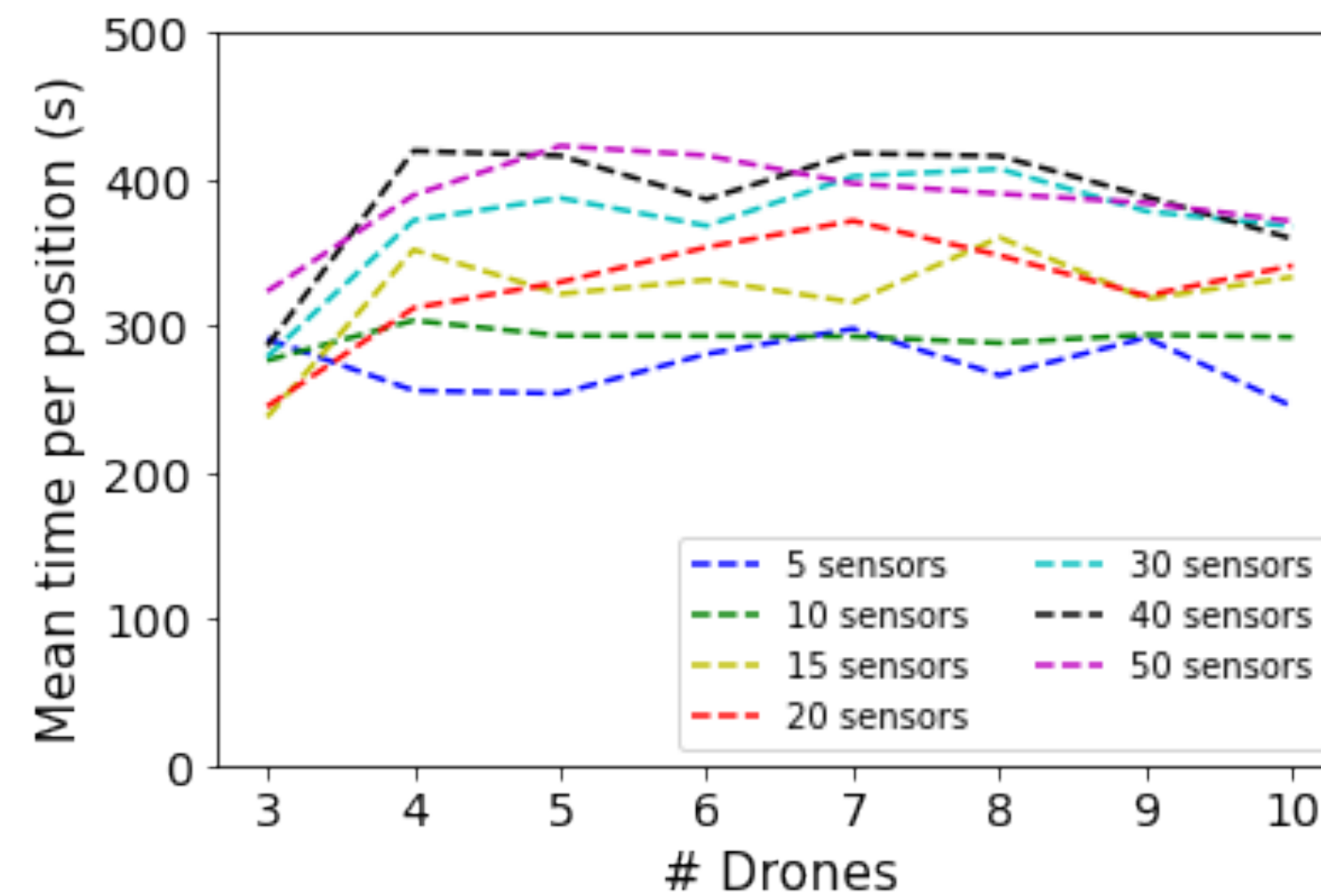
Mean number of positions each drone



Mean altitude of the positions occupied

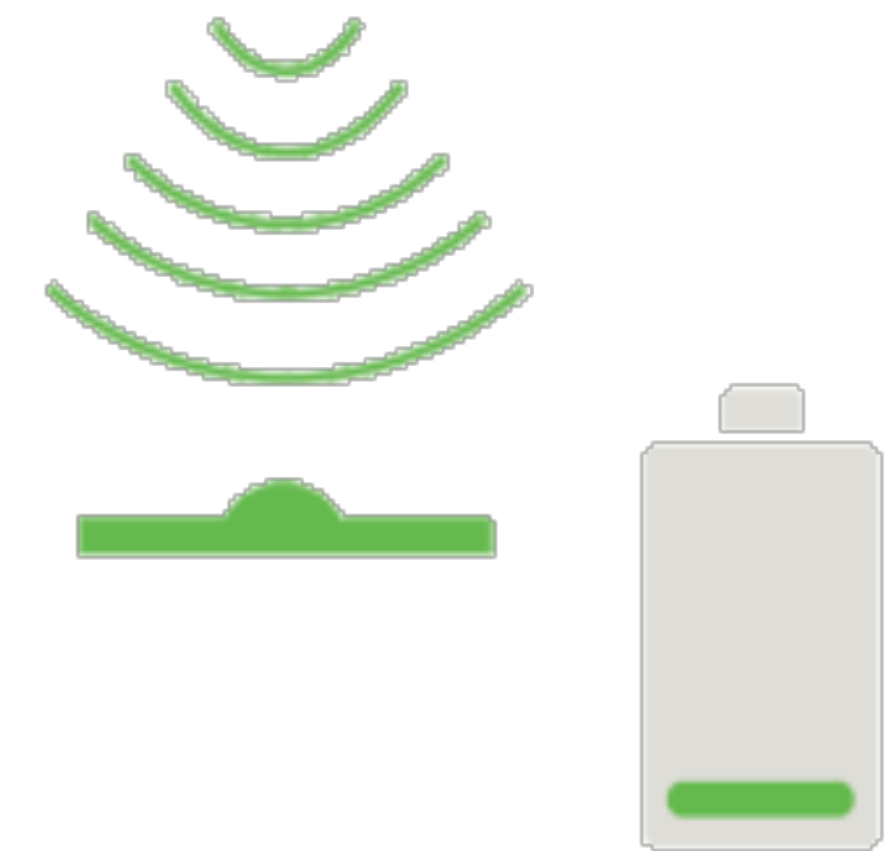
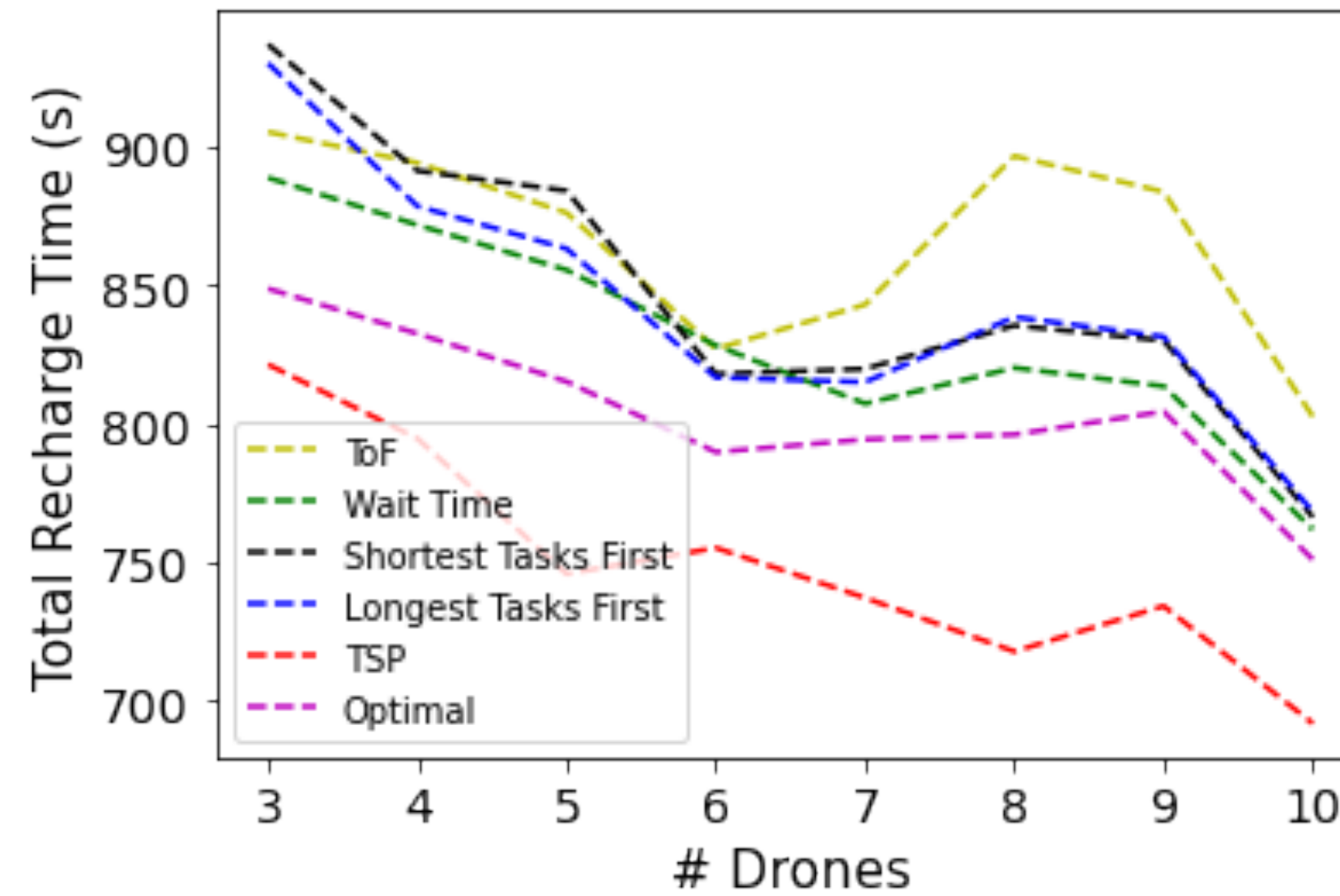


Mean time spend at the same positions

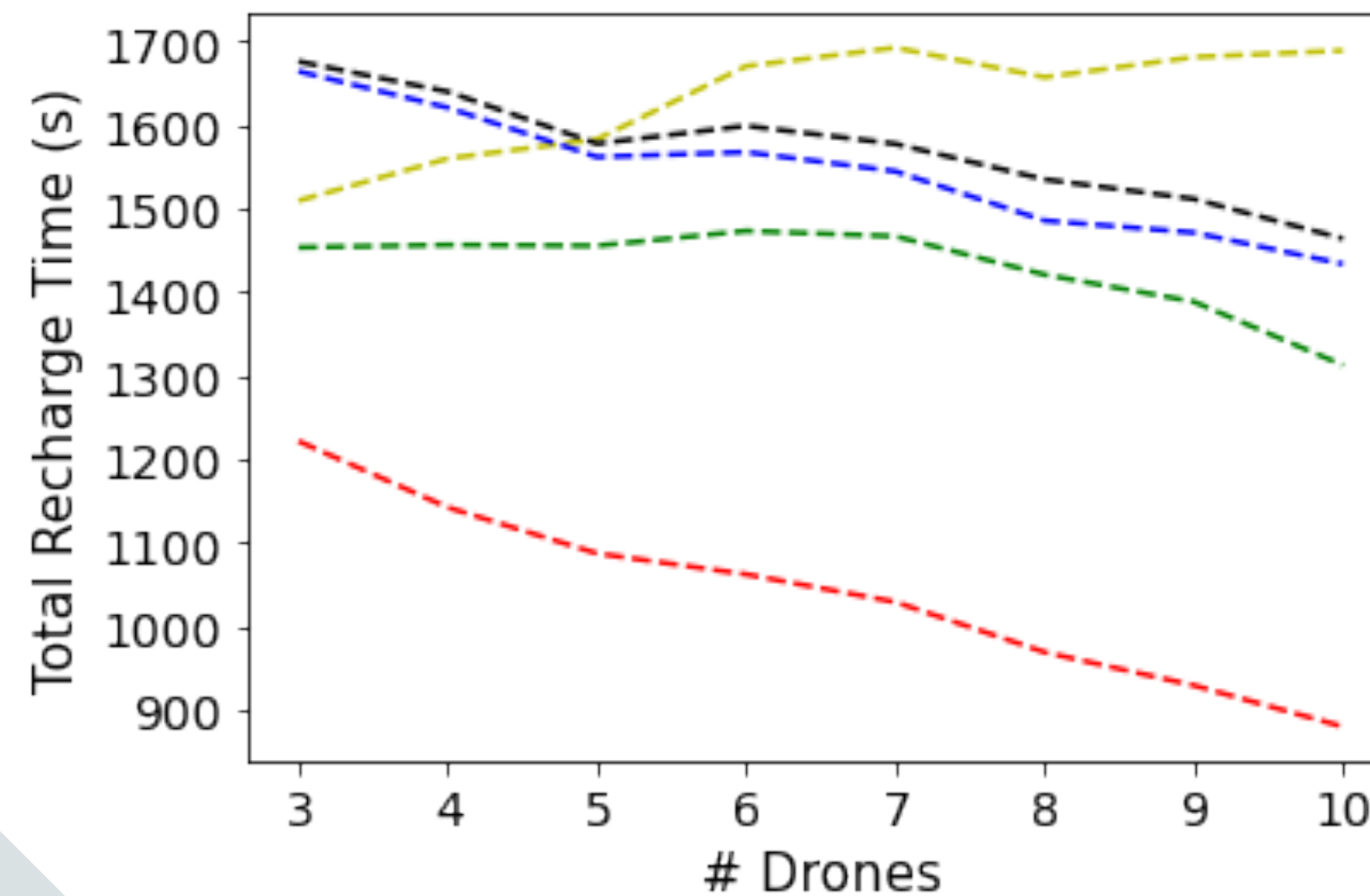


# PERFORMANCE EVALUATION SCHEDULING

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 Mines-Télécom

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

**THANKS FOR  
YOUR ATTENTION**

**[yann.busnel@imt-atlantique.fr](mailto:yann.busnel@imt-atlantique.fr)**

