

Spectral GNNs vs GATs

When attention is (not all you need) the "only" option

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Motivation

- Growing importance of efficient last-mile delivery logistics.
- Use of drones (Unmanned Aerial Vehicles, UAVs) for overcoming traffic constraints, reducing delivery times, and lowering operational costs.
- Significant increase in literature on Delivery Drones in recent years [1].

Introduction to Last-Mile Delivery Drones

Figure: Drones Congestion
in a high-traffic Last Mile
Delivery context.

Source: [4]



Introduction to Last-Mile Delivery Drones

Last Mile Delivery Drones (LMDD)

- Heterogeneous research area:
 - Combining drones and trucks.
 - Linear integer modeling.
 - Fuzzy logic for uncertainties.
 - Multi-objective optimization.
 - Exclusive drone-based solutions.
- **Complex Systems Decentralized Approach:**
 - Tradable permit model for multi-agent airspace use [5].

Related Work and Centralized Control

- **Necessity of Air Traffic Management:**
 - Most centralized models don't address collision avoidance [1].
 - Ensuring optimal path planning and efficient airspace control.
- **Centralized Control and UTM:**
 - **Centralized Control:**
 - Federal Aviation Administration (FAA) and NASA's Unmanned Aircraft System Traffic Management (UTM) [2].
 - Ensures organized, legislative-backed airspace control.
 - **Decentralized Models:**
 - Novel but complex in scalability and regulatory compliance.

Proposed Approach

- **Aispace Control and MAPF Approach:**
 - Multi-Agent Path Finding (MAPF) is a solution for addressing spatial characteristics and collision avoidance.
- **Proposed Strategy:**
 - Employing MAPF strategy for Last Mile Delivery Drone problem.
 - Three approaches: MILP, heuristic and hybrid.
 - Use of prioritized planning [10] and conflict-based search [3] to manage computational complexity in the heuristic.
 - Comparing the MILP with the heuristic.
 - Qualitative comparison between centralized and decentralized approaches.

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LMDD as MAPF

- Tasks for each agent (drone) described by tuples:

$$\text{task}_i := \{(x_{\text{start}_i}, y_{\text{start}_i}), (x_{\text{goal}_i}, y_{\text{goal}_i})\}, \forall \text{ drone } d_i$$

- Grid bounds: $x \leq X, y \leq Y$.
- Goal: find paths P_{d_i} making the path length as short as possible.

Path Planning and Constraints

- Drones limited to four principal movements: upward $(x, y + 1)$, downward $(x, y - 1)$, rightward $(x + 1, y)$, and leftward $(x - 1, y)$.
- Adjacency: (x_1, y_1) is adjacent to $(x_2, y_2) \iff |x_2 - x_1| + |y_2 - y_1| = 1$.
- New decision variable: t_{begin} (arrival time).

LMDD Goals

- Given time T , minimize the sum of distances of all drones.
- Allow drones to wait in cells and choose entry time.
- Non-weighted distances make the problem easier than standard MAPF.

Network Flow Problem

- MAPF is equivalent to multi-commodity minimum cost maximum flow problem [9].
- Visualized as Network Flow problem.
- The number of drones is a max flow in the time-expanded net

MAPF as Network Flow Problem

- Transformation into a time-expanded network [8].

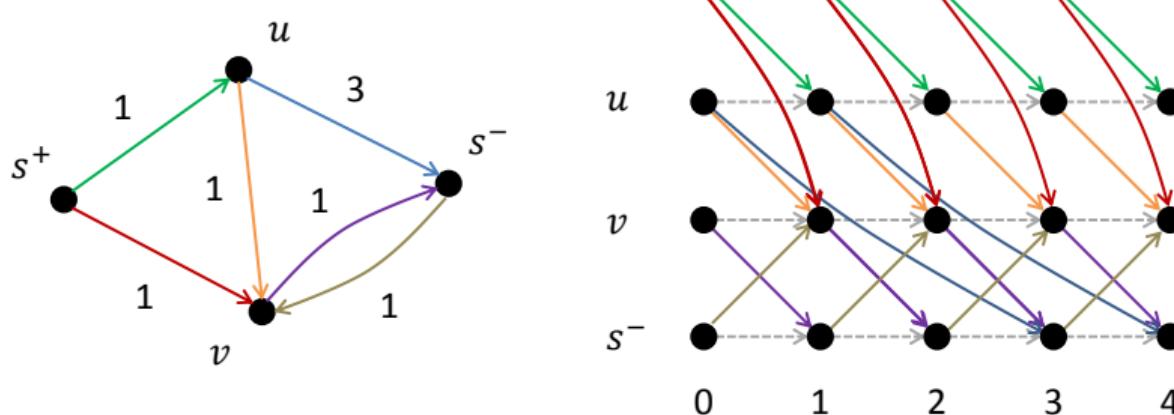


Figure: Time-expanded network representation (sourced from [7])

Multi-Commodity Flow Formulation

- Each drone is a separate commodity flowing from start to goal node.
- Ensuring each drone reaches its goal within a given time horizon T .

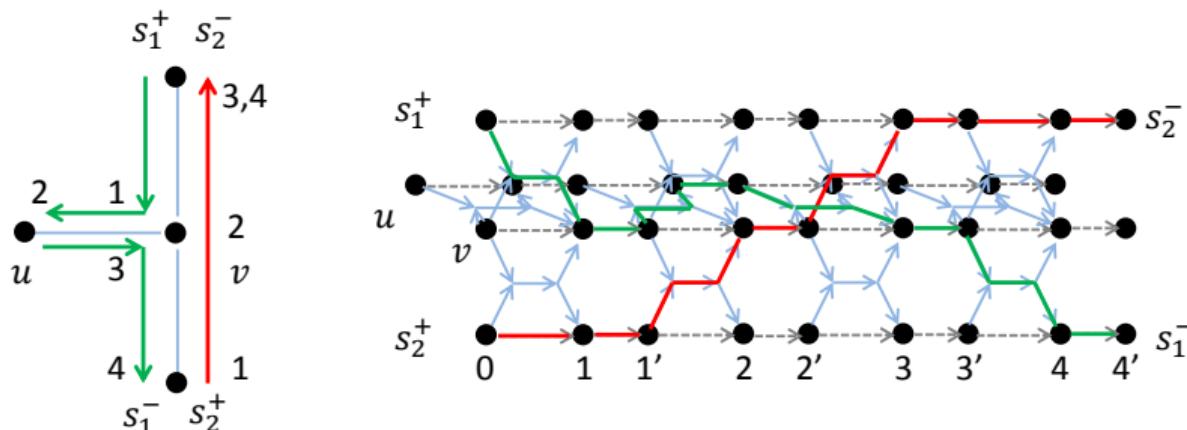


Figure: Equivalence of MAPF to multi-commodity network flow (sourced from [7])

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MILP Model - Graph Modelling

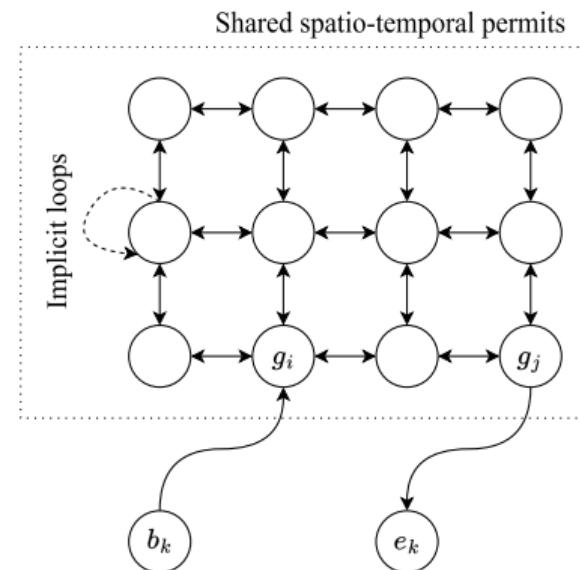
- Proposal of a Mixed-Integer Linear Programming (MILP) model to solve the problem.
- Graph construction representing spatio-temporal permits shared by the drones.
- Modeled as a directed graph (digraph) $G = (V, A)$.
- V : set of nodes representing airspace and virtual drone locations.
- A : set of directed arcs representing permitted transitions between nodes.

MILP Model - Virtual Nodes

- Source node b_k : Starting point of drone k 's mission.
- Sink node e_k : Ending point of drone k 's mission.
- Focus on spatial topology, omitting temporal component.

Figure: Graph modelling.

Source: The authors.



MILP Model - Parameters

- T : Maximum time allowed for the mission.
- b_k : Initial virtual vertex representing the initial position of drone k .
- e_k : Final virtual vertex representing the final position of drone k .
- \mathcal{R} : Set of drones.
- \mathcal{G} : Digraph $(\mathcal{V}, \mathcal{A})$ representing the airspace.
- \mathcal{V} : Set of vertices of \mathcal{G} .
- $\mathcal{B} \subset \mathcal{V}$: Set of initial virtual vertices b_k .
- $\mathcal{E} \subset \mathcal{V}$: Set of final virtual vertices e_k .
- \mathcal{S} : Set $\mathcal{V} \setminus (\mathcal{B} \cup \mathcal{E})$.
- \mathcal{A} : Set of arcs $(i, j) \in \mathcal{A}$ of \mathcal{G} .

MILP Model - Variables

- Decision Variables:
 - $x_{i,j,t}^k = 1 \iff$ drone k jumps from i to j at time t .
- Indices:
 - k : Drone $\implies k \in \mathcal{R}$.
 - t : Time $\implies 1 \leq t \leq T$.
 - i, j, l : Vertices $\implies i, j, l \in \mathcal{V}$.

MILP Model - Objective Function

- Minimize the total sum of the number of drone movements:

$$\min \sum_{k \in \mathcal{R}} \sum_{t=1}^T \sum_{(i,j) \in \mathcal{A}: j \notin (\mathcal{E} \cup \mathcal{B})} x_{i,j,t}^k$$

- Minimize the total number of drone movements, counting $n - 1$ jumps for each drone that performs n jumps.

MILP Model - Constraints

- Ensure each drone starts its mission:

$$\sum_{t=1}^T \sum_{j \in \mathcal{S}} x_{b_k, j, t}^k = 1, \quad \forall k \in \mathcal{R}$$

- Flow conservation:

$$\sum_{j \in \mathcal{V}} x_{i, j, t-1}^k = \sum_{l \in \mathcal{V}} x_{j, l, t}^k, \quad \forall j \in \mathcal{V}, \forall k \in \mathcal{R}, \forall t \in \{2, \dots, T\}$$

MILP Model - Constraints (Cont.)

- Border condition at time $t = 0$:

$$x_{i,j,0}^k = \begin{cases} 1, & \text{if } i = b_k \wedge j = b_k, \\ 0, & \text{otherwise.} \end{cases} \quad \forall k \in \mathcal{R}, \forall (i,j) \in A$$

- Mutual exclusion of vertex occupation:

$$\sum_{k \in \mathcal{R}} \sum_{j \in \mathcal{V}} x_{i,j,t}^k \leq 1, \quad \forall j \in \mathcal{V}, \forall t \in \{1, \dots, T\}$$

MILP Model - Mission Accomplishment

- Ensure each drone completes its mission:

$$\sum_{t=1}^T \sum_{i \in \mathcal{S}} x_{i,e_k,t}^k \geq 1, \quad \forall k \in \mathcal{R}$$

Heuristic Approach

- Utilize distance measure as heuristic metric [6].
- Organize drones in ascending order (prioritized planning) based on start and end points.
- Employ iterative Breadth-First Search (BFS) on temporal graph.
- Dynamic constraints update of occupied positions (conflict-based search).
- Combine heuristic sorting and iterative BFS for efficient path planning and adaptability.

Algorithm Notation

Table: Notation used in the Algorithm.

Notation	Definition
\mathcal{V}	Set of vertices in the graph : (i, j, t)
\mathcal{E}	Set of edges
\mathcal{D}	Set of drones
\mathcal{S}	Set of already scheduled vertices
$\mathcal{P}_d \subseteq \mathcal{V}$	Path of drone d
$\mathcal{G} = (\mathcal{V}, \mathcal{E})$	Temporal Graph

Heuristic Algorithm Steps

- ① **Drones Sorting:** Ascending sort using Euclidean Distance.

$$\mathcal{D}_{\text{sorted}} = \text{sort}(\mathcal{D}, \text{heuristic}) \quad (1)$$

- ② **Path for Each Drone:** Compute path P_d using BFS on graph \mathcal{G} .

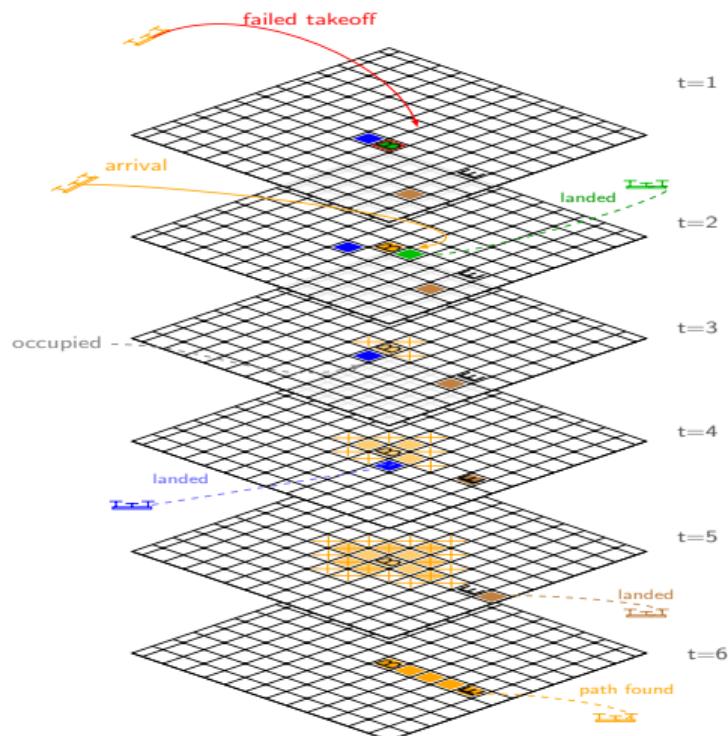
$$\forall d \in \mathcal{D}_{\text{sorted}} : \quad \mathcal{P}_d = \text{BFS}(\mathcal{G}, d) \quad (2)$$

- ③ **Constraints Update:** Update set of already scheduled vertices \mathcal{S} .

$$\mathcal{S} = \mathcal{S} \cup \bigcup_{d \in \mathcal{D}_{\text{sorted}}} \mathcal{P}_d \quad (3)$$

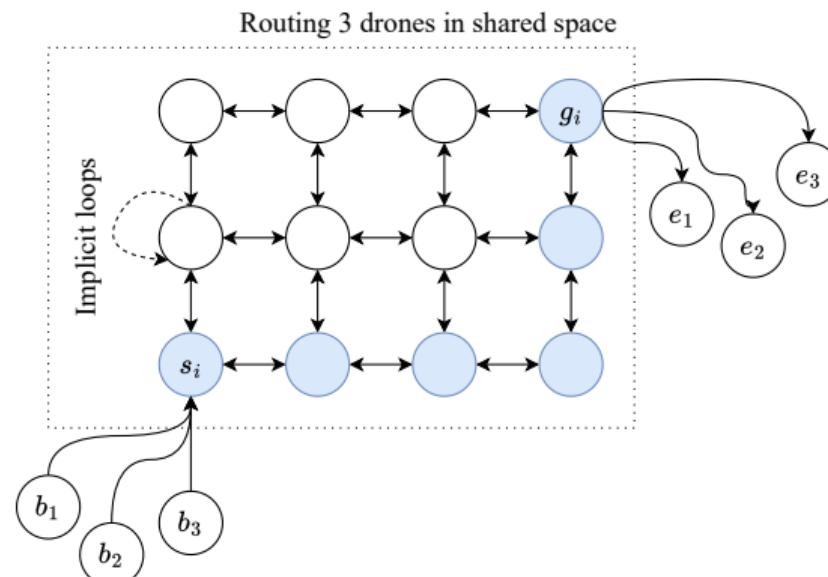
Algorithm Visualization

Figure: Algorithm visualization.
Source: The authors.



Complexity Analysis and Boundedness

- Worst-case complexity: $\mathcal{O}((N + M)KNM \log((N + M)KNM))$.
- Approximation: $\mathcal{O}(N^3K \log(N^3K))$ for square grids.



Hybrid Methodology

- **Heuristic Solution Generation**
 - Quickly generates an initial feasible solution.
 - Determines a plausible time horizon $T_{\text{heuristic}}$.
- **MILP Model Refinement**
 - Uses $T_{\text{heuristic}}$ and initial feasible solution from heuristic.
 - Refines the solution to ensure global optimality.
- **Advantages**
 - Combines computational speed with solution accuracy.
 - Skips multiple iterations to determine T , reducing computational expense.

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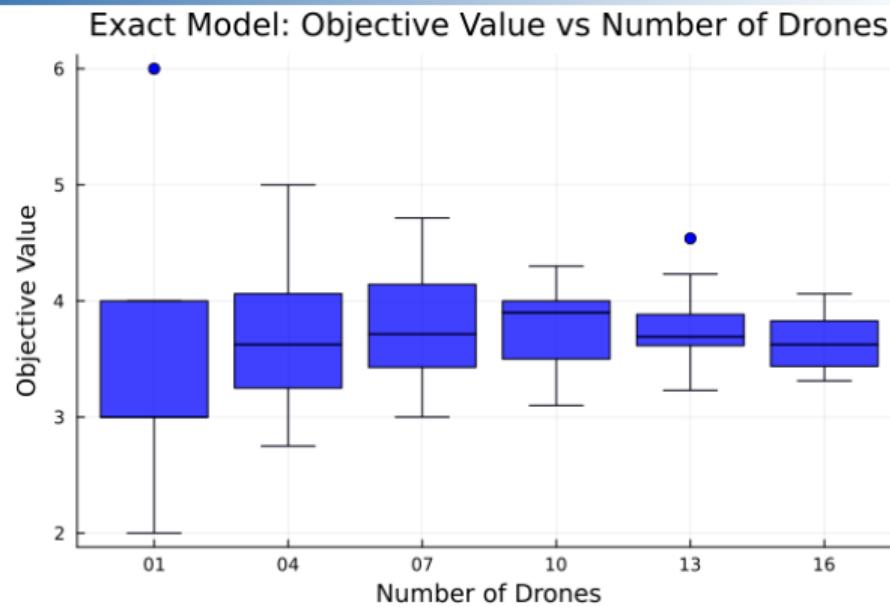


Figure: Exact Model Objective. Source: The authors.

Results

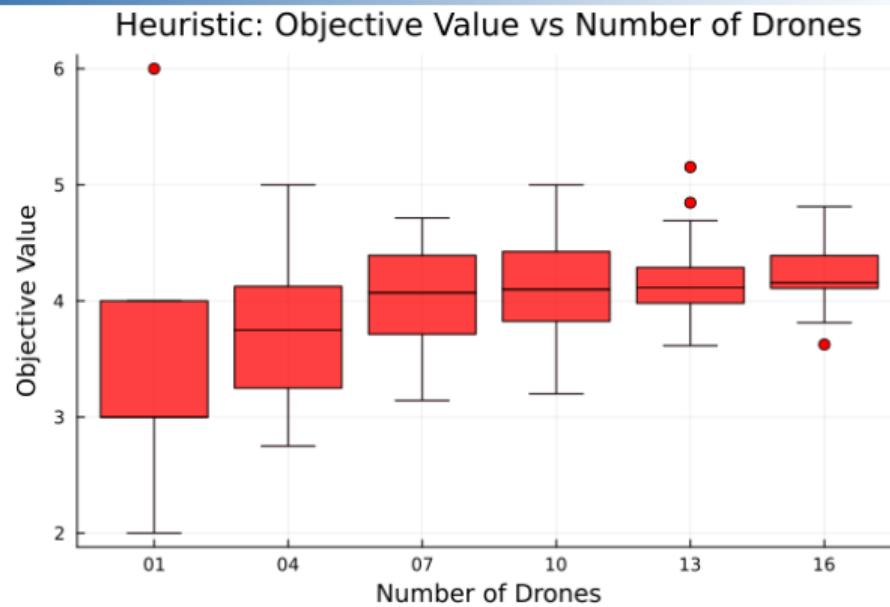


Figure: Heuristic Objective. Source: The authors.

Results

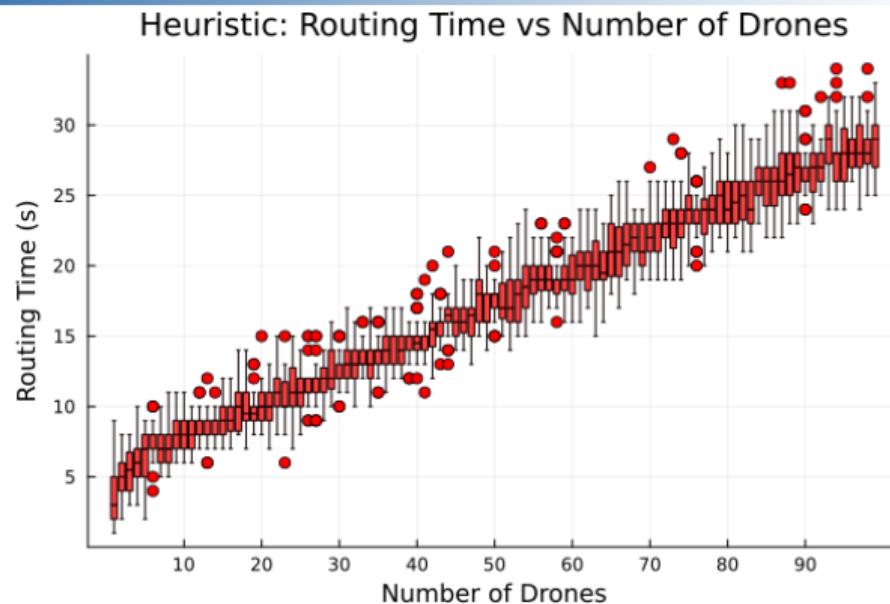


Figure: Heuristic Routing Time (T) corresponding to Figure ???. Source: The authors.

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Advancements

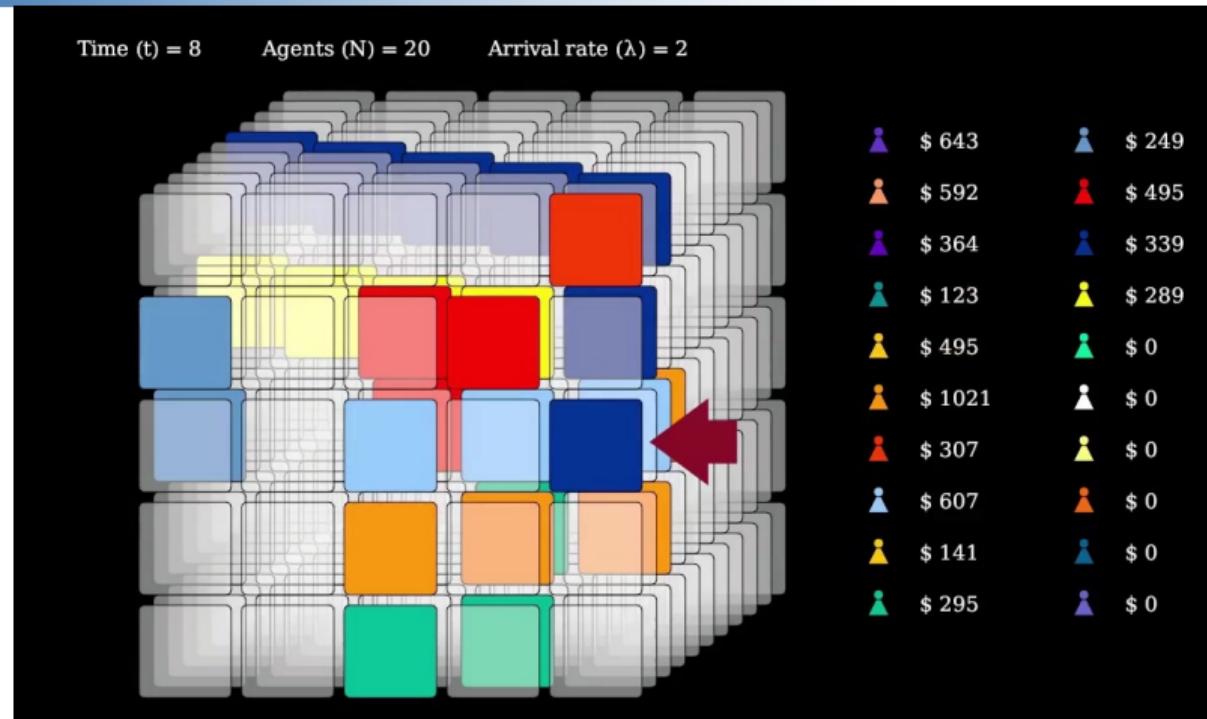
- Addressing the Last Mile Delivery Drones problem through a MAPF approach ;
- Ensuring collision avoidance and efficient airspace control.
- Significant advancement over previous algorithms with guaranteed finite and bounded polynomial time convergence for the heuristic

Limitations

- Does not address real world problems like energy, fuel and speed of the drones;
- The experiment using binary search to find the T for the MILP in $\mathcal{O}(\log(T))$ is not conducted;
- Small grid sizes in experiments;

Future Works

Figure: Tradable Permit Model in the Decentralized LMDD.
Source: [5]



Future Works

Decentralized Model from [5]

- naive agents
- greedy random choices

Decentralized Model with Intelligence

- Reinforcement Learning
- Graph Dynamical System
 - Complex Networks
 - Graph Neural Networks

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