



SLIM: Scheduling Deadline-Driven Tasks with a Minimum Number of UAVs

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Outline

- 1 Introduction**
- 2 Problem
- 3 Algorithm
- 4 Simulation
- 5 Conclusion

Background

Problem

Algorithm

Simulation

Conclusion

Agriculture



Power line



Forest



Medicine



Background

Problem

Algorithm

Simulation

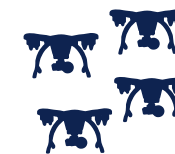
Conclusion



Time-sensitive tasks

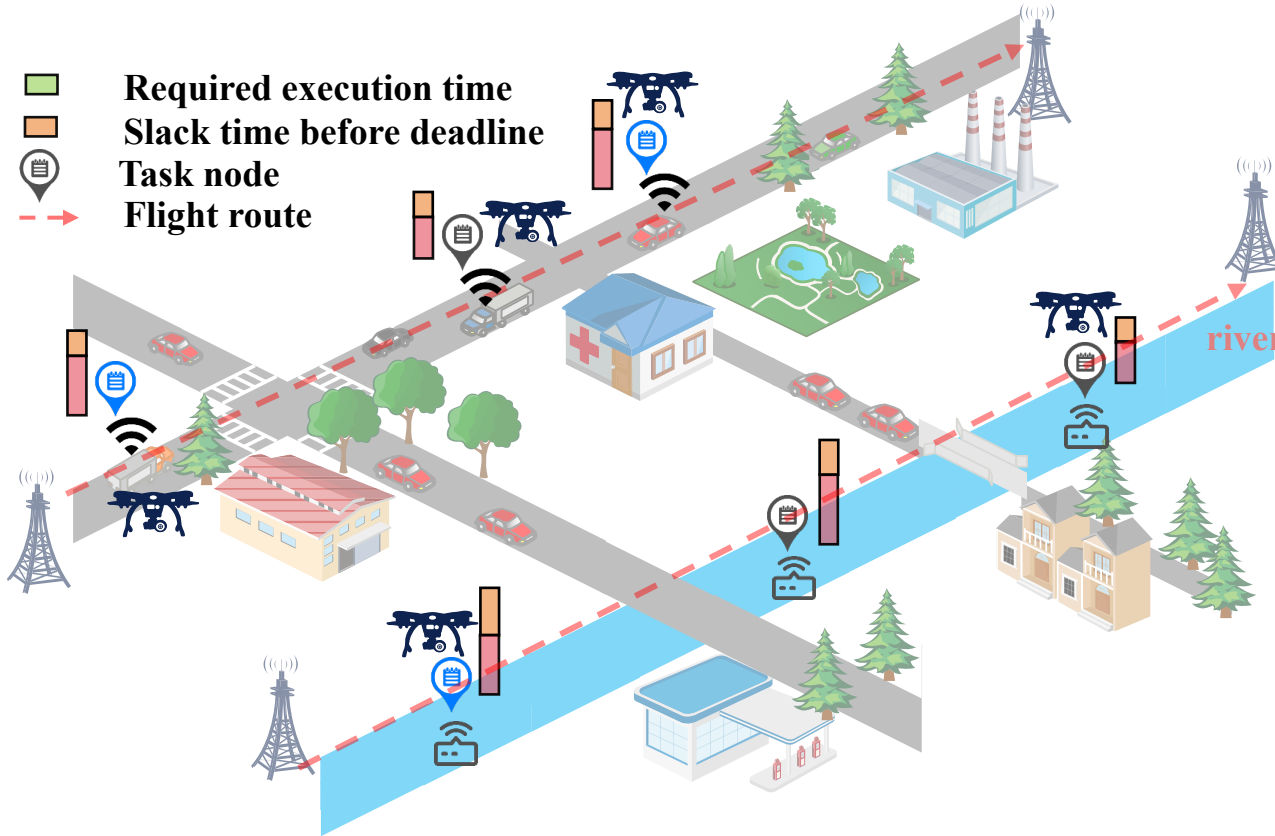


Limited-capability single UAV



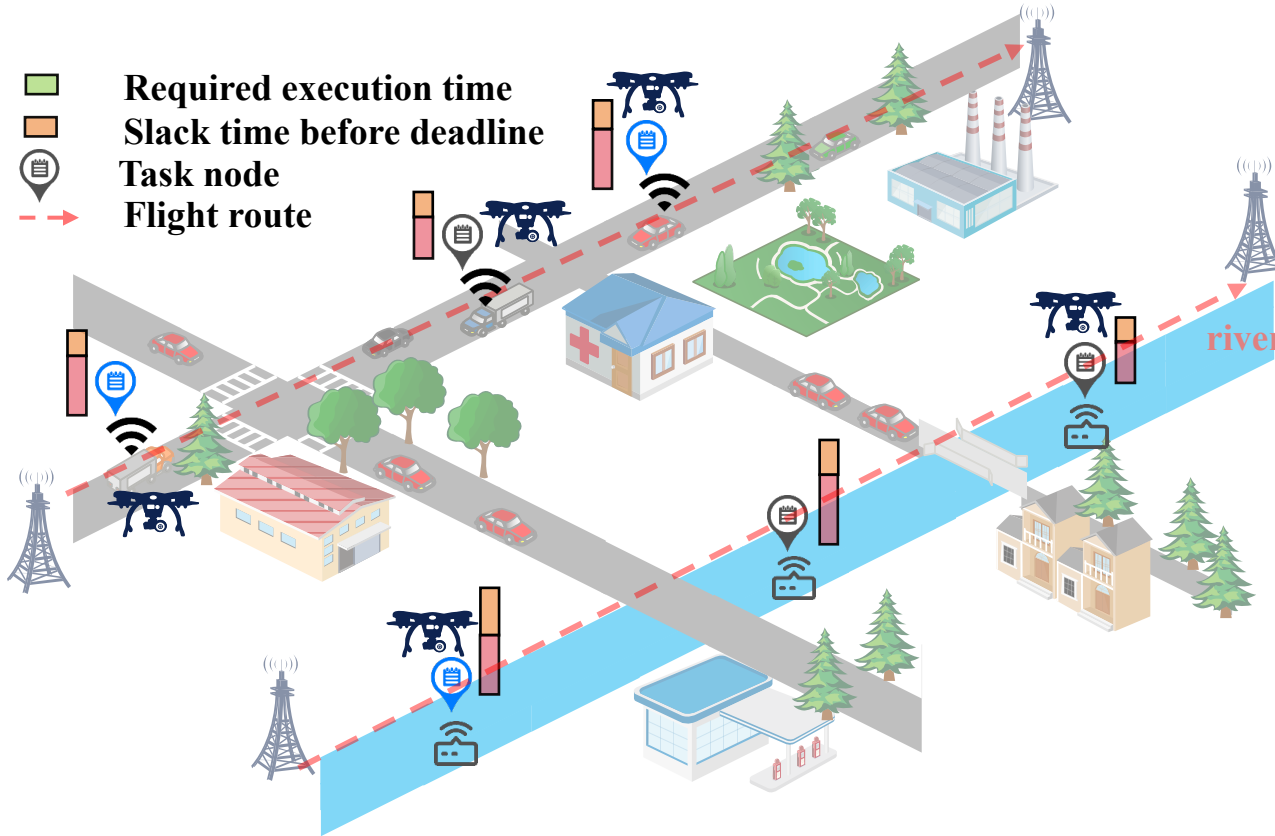
Multi-UAV task scheduling system









Limitations




- Fixed number of UAVs
- ✗ Insufficient UAVs → Task failure
- ✗ Excessive UAVs → Resource waste
- 👎 **No work** focuses on minimizing UAVs for deadline-constrained tasks



Limitations

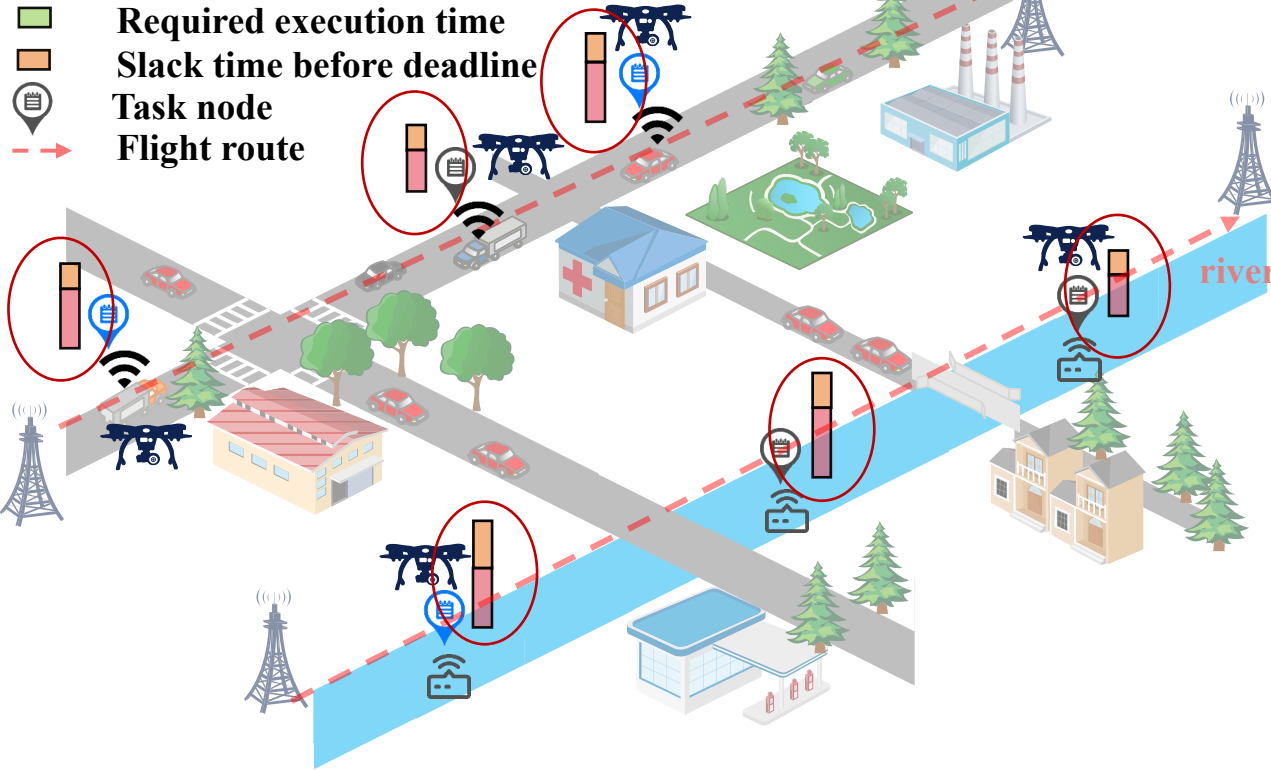
-  Fixed number of UAVs
-  Insufficient UAVs → Task failure
-  Excessive UAVs → Resource waste
-  **No work** focuses on minimizing UAVs for deadline-constrained tasks

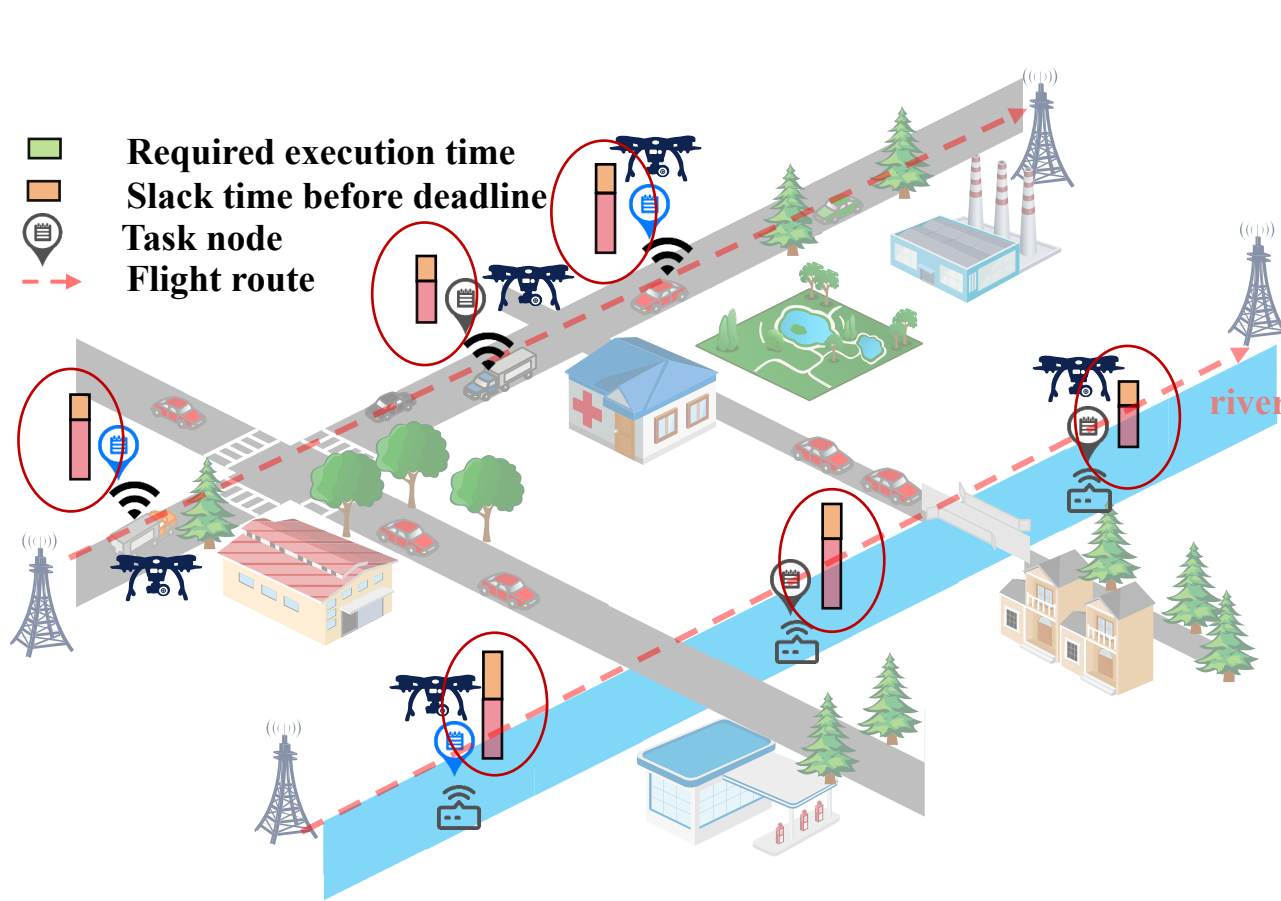
Our contribution

-  Scheduling deadline-driven tasks with a minimum number of UAVs (**SLIM**):
-  Deadline-driven tasks
-  The number of UAVs minimization



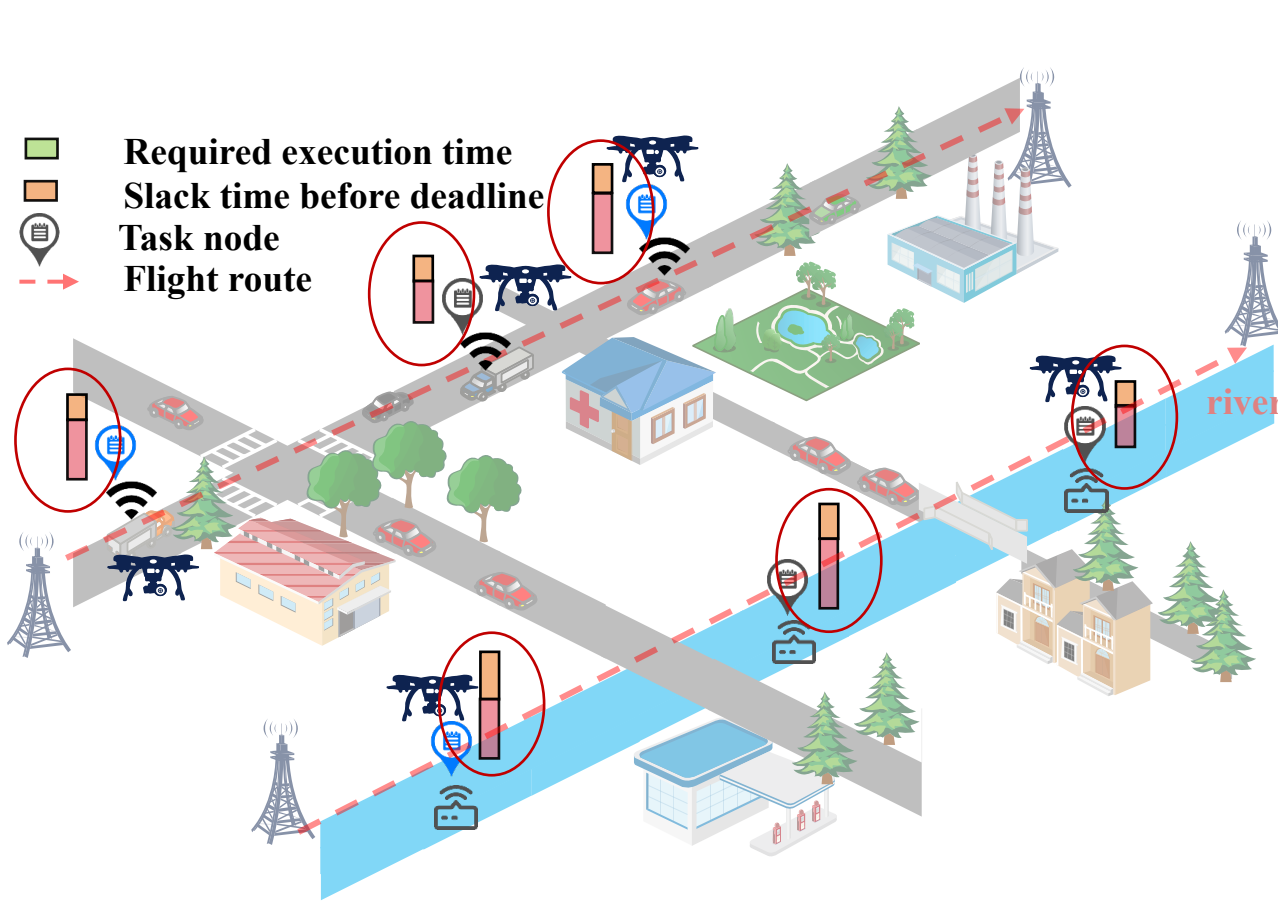
Challenges





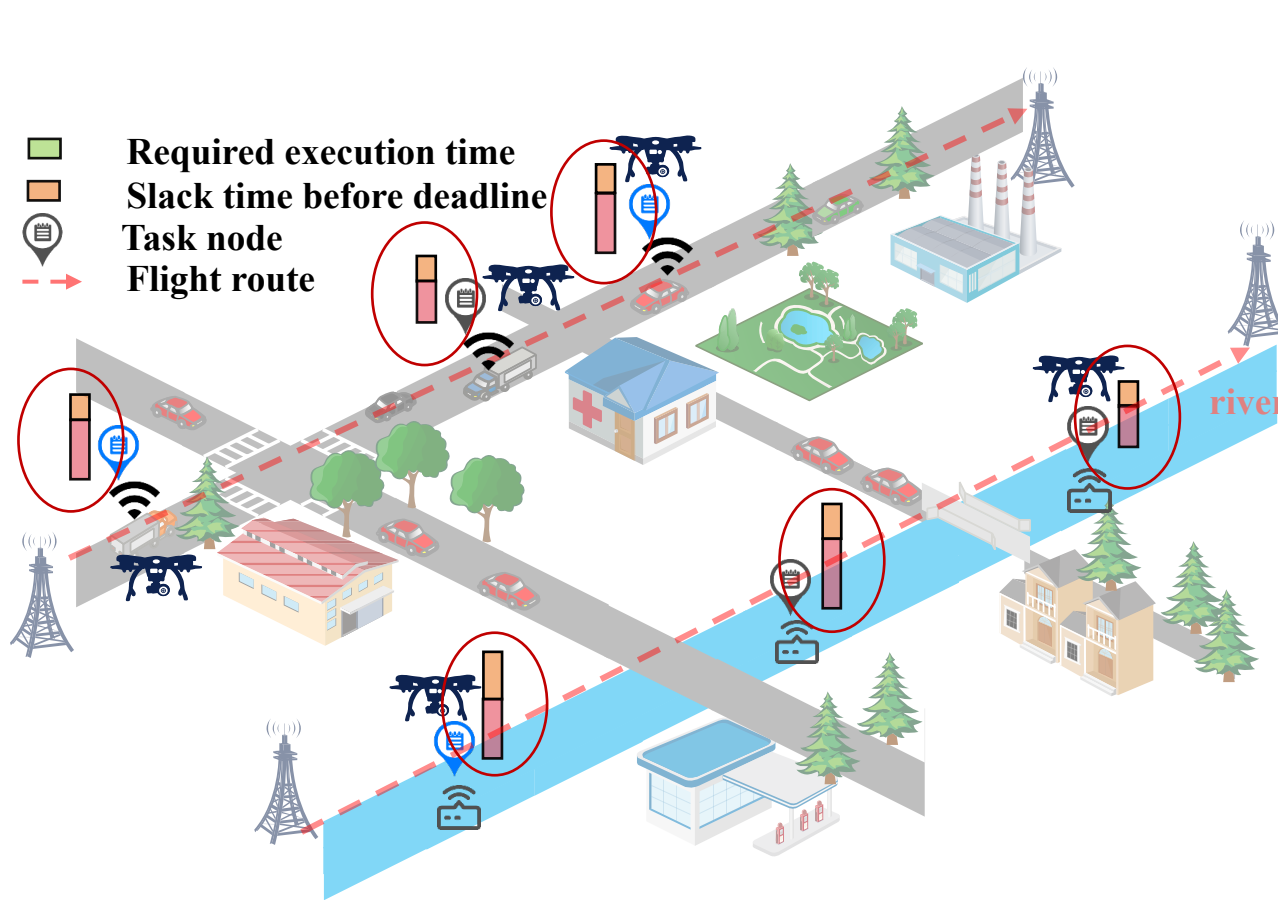
Challenges

- How to minimize the required number of UAVs while meeting all tasks' deadlines?



Challenges

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- How to decide task execution decisions, even when the number of UAVs is known?



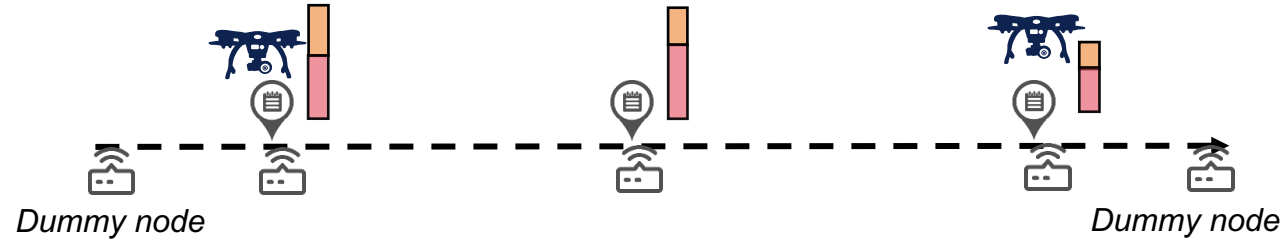
Challenges


- How to minimize the required number of UAVs while meeting all tasks' deadlines?
- How to decide task execution decisions, even when the number of UAVs is known?
- How to design an optimal task schedule, even for a single UAV?


Outline


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System Model



 UAV set $U = \{u_1, u_2, \dots, u_M\}$


 Task set $P = \{p_1, p_2, \dots, p_n\}$

 Task attributes $p_k(q_k, d_k), \delta_k = d_k - q_k \geq 0$

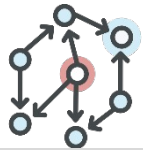
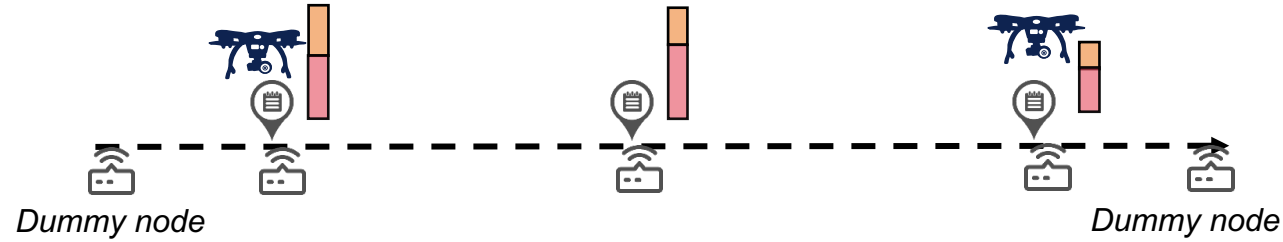
Slack time

Deadline

Required time

 Decision variable $x_{i,j,k} = \begin{cases} 1, & u_i \text{ executes } p_k \text{ after } p_j, j < k, \\ 0, & \text{others.} \end{cases}$

System Model



Task constraints

$$\sum_{k=1}^n x_{i,0,k} = 1, \sum_{j=1}^n x_{i,j,n+1} = 1, \forall u_i \in U.$$

Dummy node constraint

$$\sum_{j=0}^{l-1} x_{i,j,l} = \sum_{k=l+1}^{n+1} x_{i,l,k}, \forall p_l \in P, \forall u_i \in U.$$

In-out-degree constraint

$$\sum_{i=1}^{\mathcal{M}} \sum_{j=0}^{k-1} x_{i,j,k} = 1, \forall p_k \in P.$$

Task execution constraint

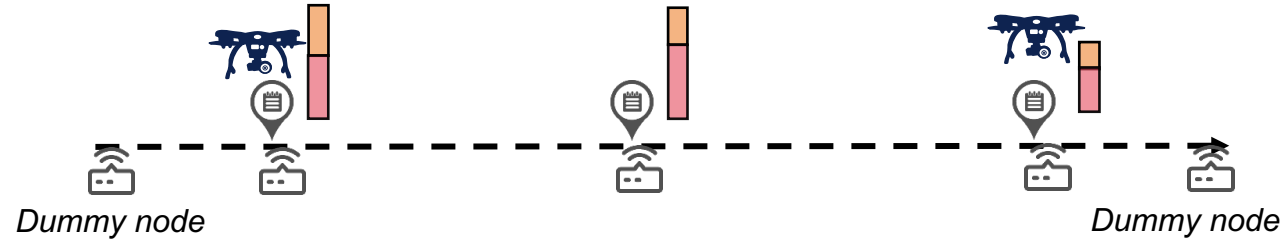
$$t_{i,k} + q_k \leq d_k, \forall u_i \in U, \forall p_k \in P.$$

Task deadline constraint

$$(t_{i,j} + q_j + \tau_{j,k} - t_{i,k})x_{i,j,k} \leq 0, \forall u_i \in U, \forall p_k \in P, j < k.$$

Execution time constraint

System Model



Energy constraint

$$\mathcal{E}_e^i = \eta \sum_{k=1}^{n+1} \sum_{j=0}^{k-1} x_{i,j,k} q_k, \forall u_i \in U.$$

$$\mathcal{E}_f^i = \int_{t=0}^{t=T} \mathbb{P}(v(t)) dt, \forall u_i \in U.$$

$$\mathcal{E}_e^i + \mathcal{E}_f^i \leq \mathcal{E}.$$

Constraint transformation



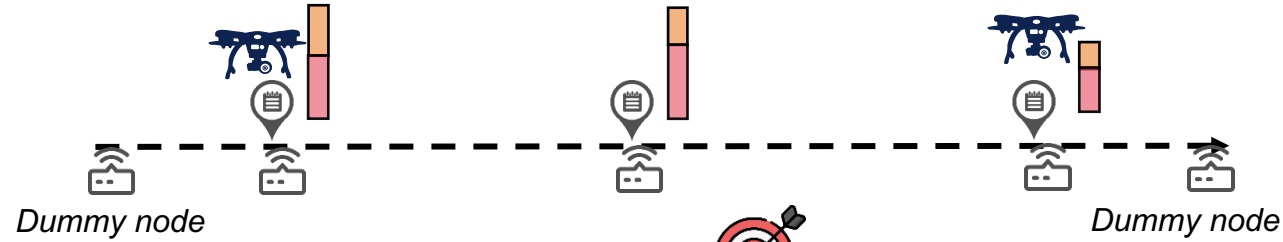
Decoupling task scheduling and UAV flight durations

$$\blacktriangleright \tau_{j,k} = \frac{d(p_j, p_k)}{v^*}, \mathcal{E}_f^* = \mathbb{P}(v^*) \frac{\sum_{k=1}^{n+1} d(p_{k-1}, p_k)}{v^*}$$

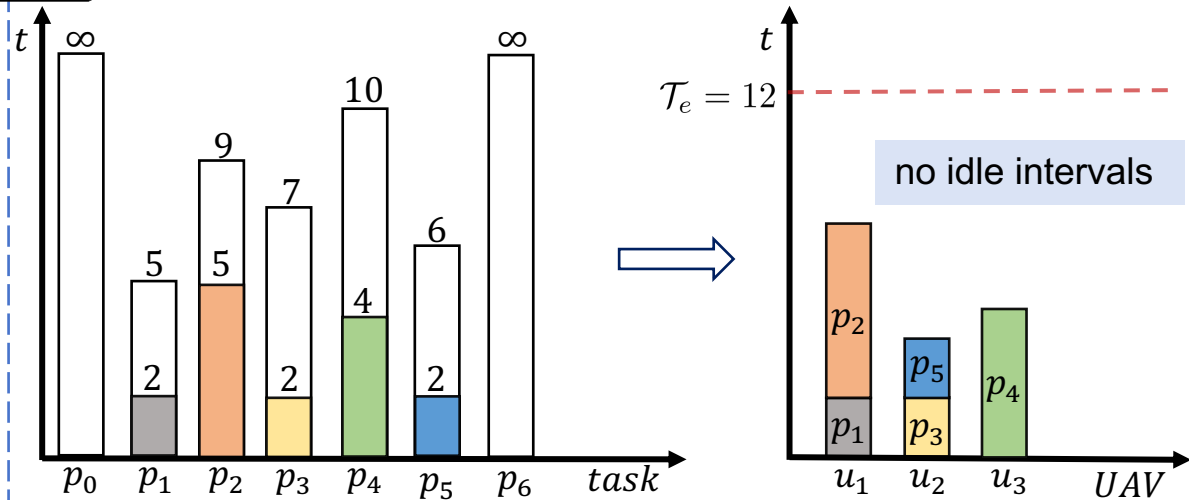
$$\blacktriangleright \sum_{k=1}^{n+1} \sum_{j=0}^{k-1} x_{i,j,k} q_k \leq \mathcal{T}_e, \mathcal{T}_e = \frac{\mathcal{E} - \mathcal{E}_f^*}{\eta}$$

$$\blacktriangleright d_k \leftarrow d_k - \sum_{j=1}^k \frac{d(p_{j-1}, p_j)}{v^*}, \forall p_k \in P$$

Problem Formulation



EXAMPLE



Objective

schedule tasks with the **minimum** number of UAVs

$$\rightarrow (\text{SLIM}) \min \sum_{i=1}^{\mathcal{M}} \sum_{k=1}^{n+1} x_{i,0,k}$$



Subject to



Task constraints + Energy constraint



SLIM problem is **NP-hard**, even when no task deadline and execution order constraints.

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SLIM-DP

- UAV workload sorting set

$$\mathcal{W} = \{W_1, W_2, \dots, W_m\}, W_1 \leq W_2 \leq \dots \leq W_m$$

- Boolean optimization function

$U(k, \mathcal{W}) \rightarrow$ Indicator for the first k tasks completion using these UAVs

- State transition equation

$$U(k, \mathcal{W}') = \bigvee_{i=1}^m \left((W_i + q_k \leq \min(\mathcal{T}_e, d_k)) \wedge U(k-1, \mathcal{W}) \right)$$

EXAMPLE

(W_1, W_2) \ task	None	p_1	p_2	p_3
(0,0)	T	F	F	F
(0, q_1)	T	T	F	F
(q_1, q_2)	T	T	T	F
(0, q_1+q_2)	T	T	T	F
(0, $q_1+q_2+q_3$)	T	T	T	T
(q_2, q_1+q_3)	T	T	T	T
(q_1, q_2+q_3)	T	T	T	T
(q_3, q_1+q_2)	T	T	T	T

DP computing table

SLIM-DP

- UAV workload sorting set

$$\mathcal{W} = \{W_1, W_2, \dots, W_m\}, W_1 \leq W_2 \leq \dots \leq W_m$$

- Boolean optimization function

$$U(k, \mathcal{W})$$

➔ Indicator for the first k tasks completion using all UAVs

- State transition equation

$$U(k, \mathcal{W}') = \bigvee_{i=1}^m \left((W_i + q_k \leq \min(\mathcal{T}_e, d_k)) \wedge U(k-1, \mathcal{W}) \right)$$

Function $\mathcal{B}(m)$:

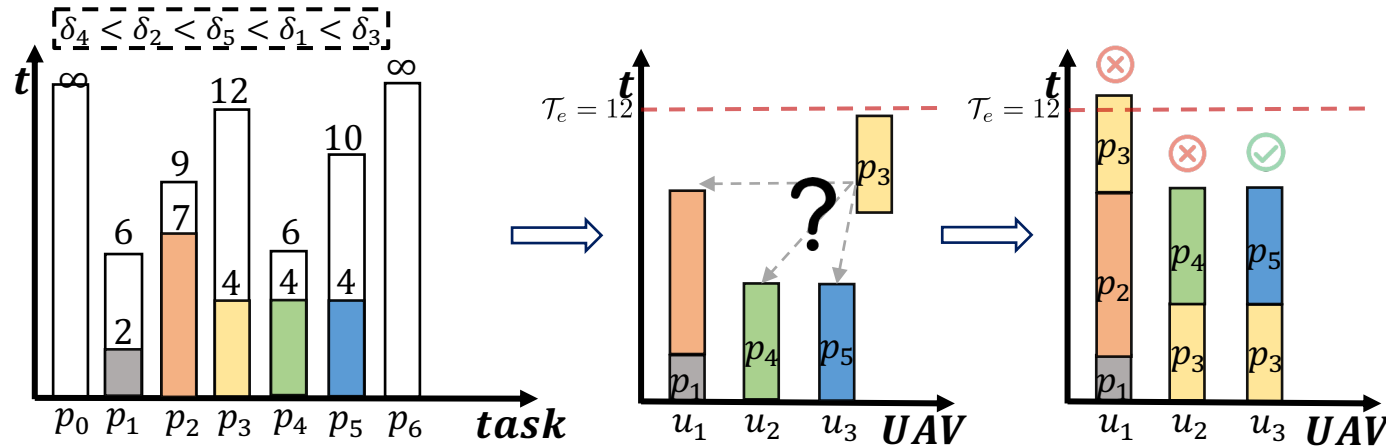
```

 $W_i = 0, i = 1, \dots, m; U(0, \mathcal{W}) = \top;$ 
for  $p_k$  ( $1 \leq k \leq n$ ) and  $\mathcal{W} \in \{\mathcal{W} | U(k-1, \mathcal{W})\}$  do
  for  $u_i$  ( $1 \leq i \leq m$ ) do
    if  $W_i + q_k \leq \min(\mathcal{T}_e, d_k)$  then
       $\mathcal{W}'_i = (W_1, \dots, W_i + q_k, \dots, W_m);$ 
       $U(k, \text{sort}(\mathcal{W}'_i)) = \top;$ 
  Return  $\exists \mathcal{W}, U(n, \mathcal{W}) = \top;$ 
 $l = 1, r = n;$ 
while  $l < r$  do
   $m = \lceil \frac{l+r}{2} \rceil;$ 
  if  $\mathcal{B}(m) = \top$  then
     $r = m - 1;$ 
  else
     $l = m + 1;$ 
return  $m;$ 

```

Bisection search for the minimum number

SLIM-AP

1
STEP

ALG(U) for **SLIM-U** Problem : UAVs have unlimited energy, removing the energy constraint.

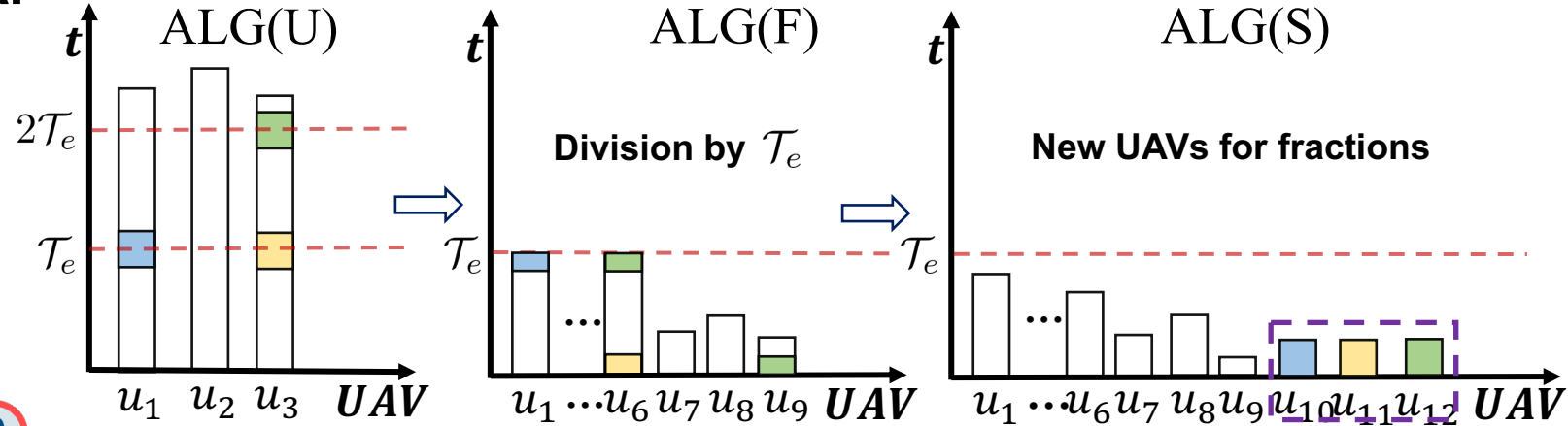
```

Let  $m = 1$  be the initial usage number of UAV;
Sort all tasks of  $P$  with non-decreasing order of slacks;
while there exists a task that is not executed do
  Let  $p_{j'}$  be the task with the smallest slack;
  for  $u_i$  ( $i = 1, \dots, m$ ) do
    if  $W_i + q_{j'} > d_{j'}$  then
      Continue;
    if appending  $p_{j'}$  to  $u_i$  causes a bad sequence then
      DO adjust sequence;
      if  $\exists p_k$  can not be executed by  $u_i$  then
        Deploy the  $m$ -th UAV;  $m = m + 1$  and break;
        Let  $u_i$  execute  $p_{j'}$  and break;
  if  $p_{j'}$  can not be executed by any UAV then
     $m = m + 1$ ;
    Deploy the  $m$ -th UAV for  $p_{j'}$ ;
return  $m$ ;

```

- Sort tasks based on slack
- Using new UAV due to
 - **Case 1:** Good sequence violation
 - **Case 2:** Deadline violation
- $ALG(U) \leq 2\alpha \cdot OPT(U), \alpha = \lceil \frac{d_{max}}{d_{min}} \rceil$

SLIM-AP

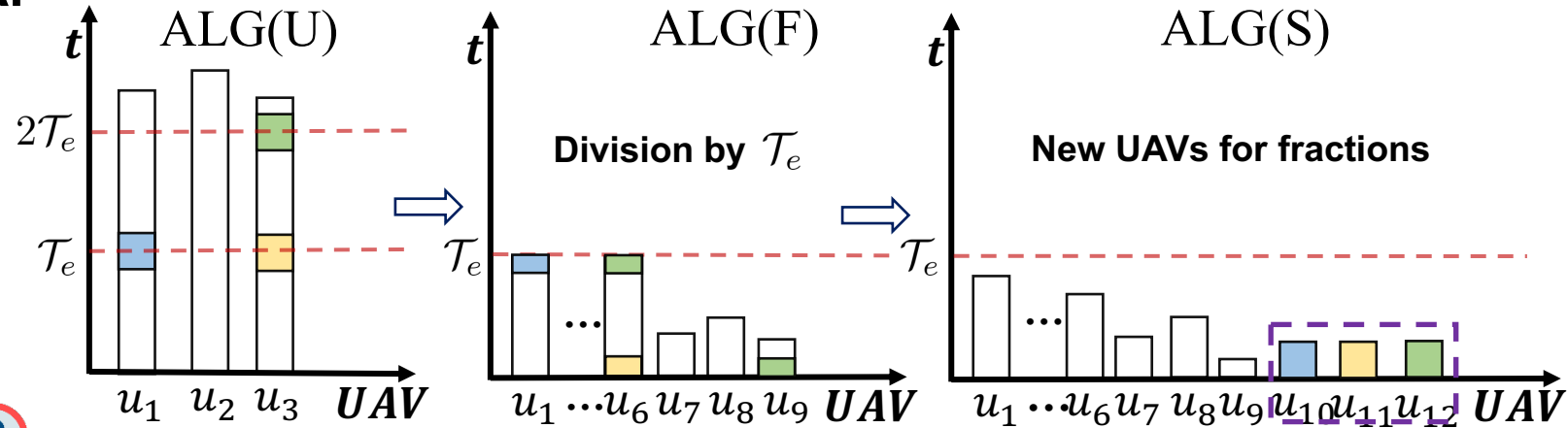


2
STEP

ALG(F) for **SLIM-F** Problem : allows fractional task execution.

- Divide workload by τ_e
- A task can be executed **by at most two UAVs**, and a UAV can provide fractional execution for **at most two tasks**
- $ALG(F) \leq \frac{\sum_{k=1}^n q_k}{\tau_e} + OPT(U)$

SLIM-AP



3
STEP

ALG(S) for SLIM Problem

- Reassign tasks with fractional execution in ALG(F) to new UAVs
- $ALG(S) \leq 2 \cdot ALG(F)$
- SLIM-AP produces a $2(2\alpha + 1)$ approximation performance of solution within $O(n^2)$ steps

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Simulation setting

- A path length of 10 km
- Power function of UAV $\mathbb{P}(v) = 0.07v^3 + 0.0391v^2 - 13.196v + 390.95$
- Varying and default parameter table

<i>Parameters</i>	<i>Values</i>		<i>Values of large scale</i>	
	default	varying/step	default	varying/step
Task number	10	[10, 20]/2	250	[250, 550]/50
UAV energy (kJ)	420	[360, 460]/20	460	[435, 465]/5
Avg task execution time (s)	50	[35, 85]10	60	[60, 150]/15
Task minimum deadline (s)	240	[90, 240]/30	240	[90, 270]/30
Task maximum deadline (s)	400			
Hovering cost (kJ/s)	0.389			
Length of flight route (km)	10			

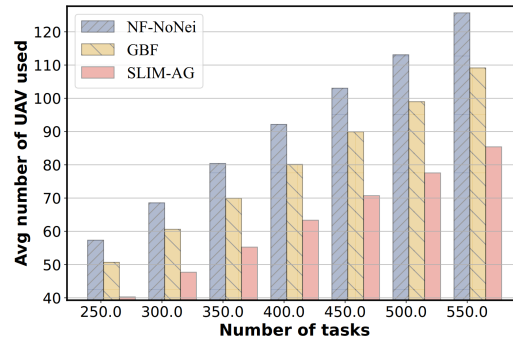
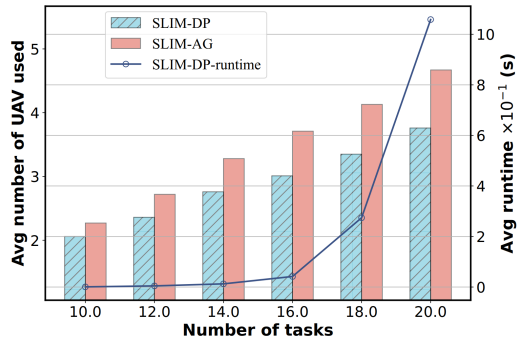
➤ Baseline

- ✓ **NF-NoNei [1]**: assigning tasks without considering deadlines, with iteratively reassigning deadline-violating tasks to new UAVs.
- ✓ **GBF [2]**: sorting tasks by non-decreasing deadlines and schedules them sequentially, with moving sequence-violating tasks to new UAVs.

[1] J. Zhang, Z. Li, W. Xu, J. Peng, W. Liang, Z. Xu, X. Ren, and X. Jia, "Minimizing the number of deployed UAVs for delay-bounded data collection of IoT devices," in *IEEE INFOCOM 2021-IEEE Conference on Computer Communications*. IEEE, 2021, pp. 1–10

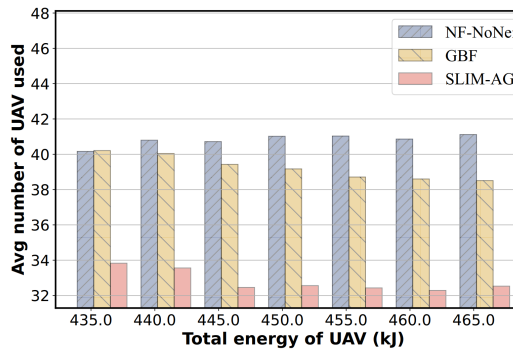
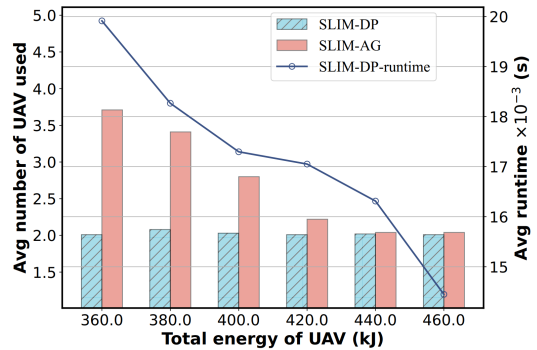
[2] M. Cieliebak, T. Erlebach, F. Hennecke, B. Weber, and P. Widmayer, "Scheduling with release times and deadlines on a minimum number of machines," in *TCS 2004-International Conference on Theoretical Computer Science*. Springer, 2004, pp. 209–222.

Simulation results



UAVs used with different number of tasks

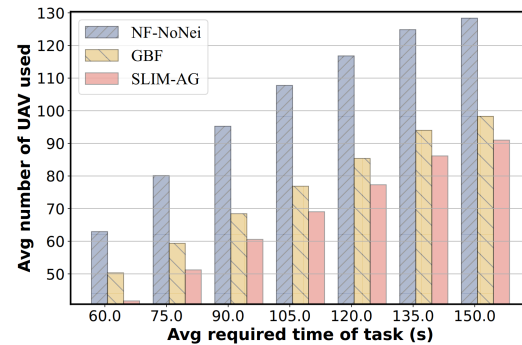
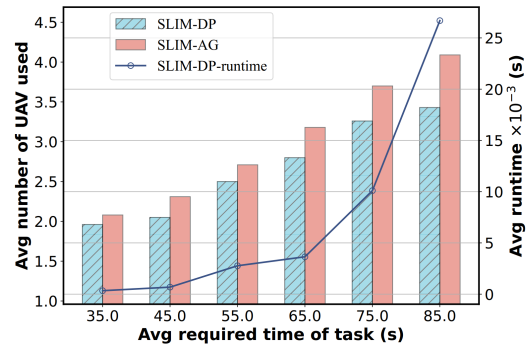
SLIM-AG shows near-optimal performance in small-scale scenarios, achieving **85%** of the optimal **SLIM-DP**, while outperforming **NF-NoNei** and **GBF** in large-scale scenarios by reducing the average number of UAVs used to **27.1%** and **45.4%**.



UAVs used with different total energy of UAV

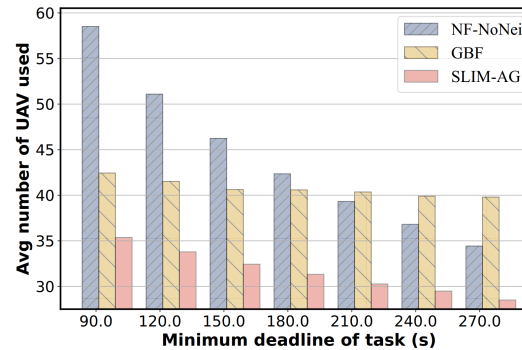
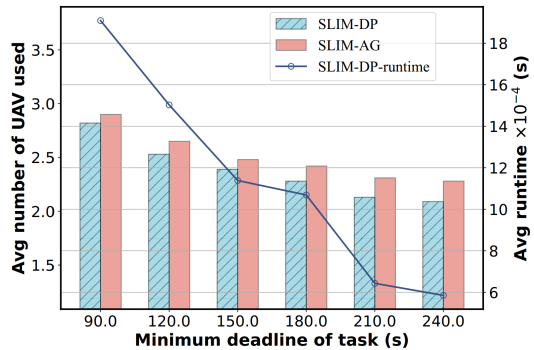
SLIM-AG maintains a performance gap with **SLIM-DP** that **narrows** as total energy increases, and it outperforms **NF-NoNei** and **GBF** in large-scale scenarios, requiring fewer UAVs as energy increases.

Simulation results



SLIM-AG continues to show strong performance, achieving **88.5%** of **SLIM-DP**'s performance in small-scale scenarios and significantly outperforming **NF-NoNei** and **GBF** in large-scale scenarios, especially as task durations increase.

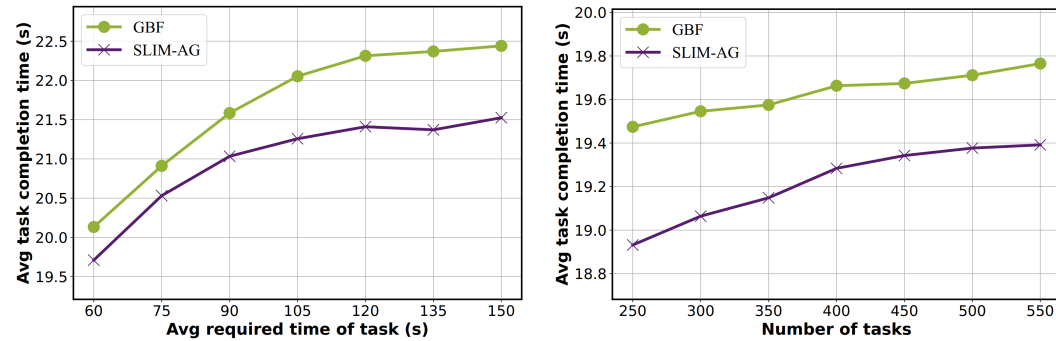
UAVs used with different required time of task



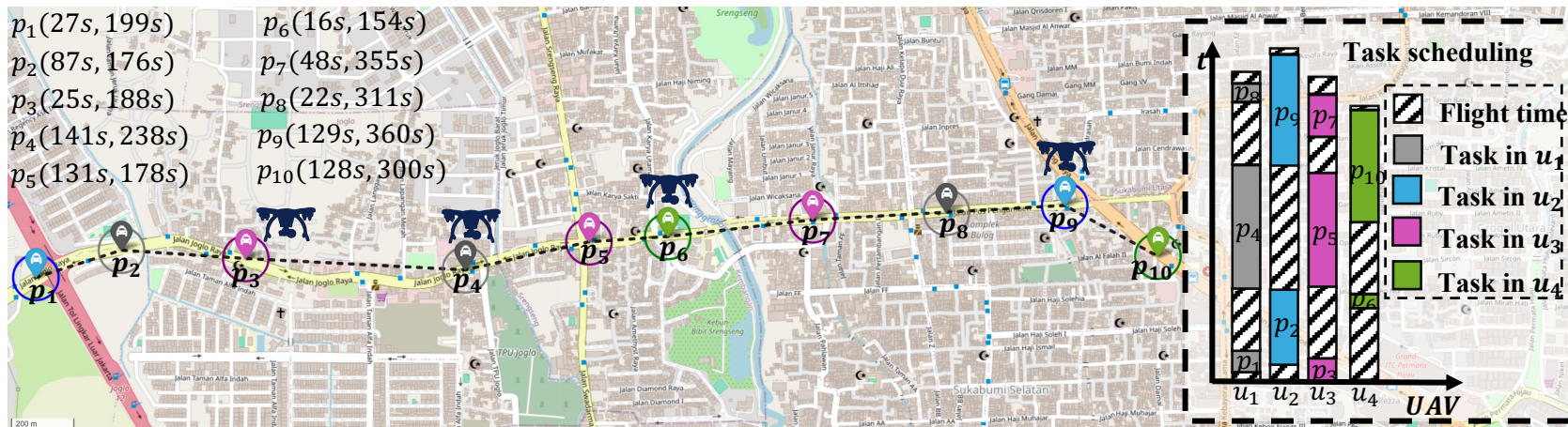
SLIM-AG has a performance gap of **only 5.6%** higher than the optimal **SLIM-DP** in small-scale scenarios, while reducing the number of UAVs by **39.6%** and **28.9%** compared to **NF-NoNei** and **GBF**, respectively.

UAVs used with different minimum deadline of tasks

Simulation results



Task completion time with different required time of task



Algorithm performance in real scenario, Jakarta bus transportation system

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- ✓ Consider the **SLIM** problem that scheduling **deadline-driven** tasks with a **minimum** number of UAVs.
- ✓ a **DP-based algorithm** that provides optimal solutions for small-scale scenarios, and an efficient **approximation algorithm** with theoretical performance guarantees for large-scale task distributions.
- ✓ Extensive simulations demonstrate that our approximation algorithm achieves about **85%** of the optimal solution's performance, while reducing the average number of UAVs by **21.8%-39.9%** compared to state-of-the-art approaches.
- ✓ Future work could explore extensions to handle dynamic task arrivals and consider additional constraints like UAV collision avoidance.

Thanks for your listening!

Q & A