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Looking before Crossing: An Optimal Algorithm to Minimize UAV Energy by Speed Scheduling with a Practical Flight Energy Model

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Outline

- Background
- Problem Modeling
- Solutions
- Simulation
- Conclusion

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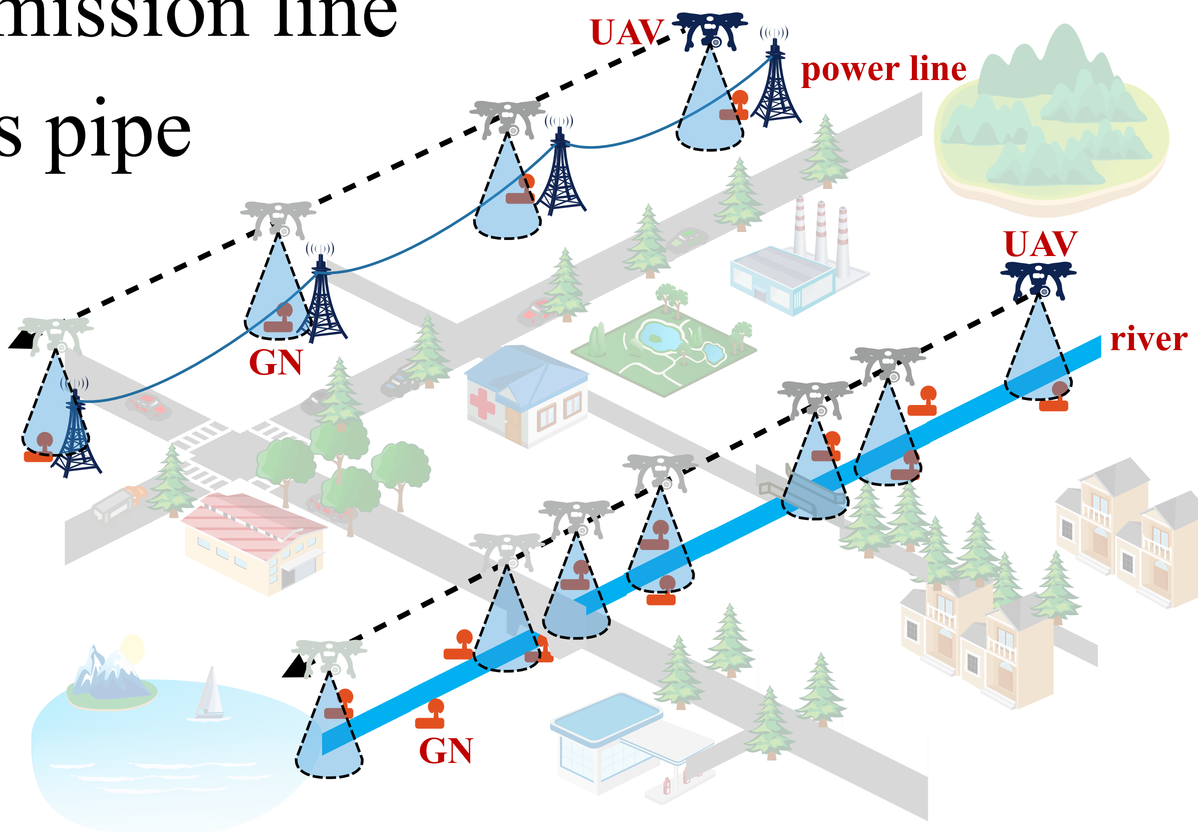
UAV data collection application scenarios

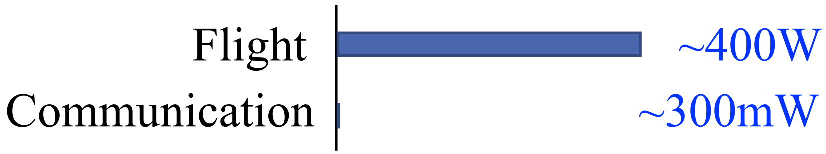
- A UAV collects data from wireless sensors or IoT devices (GNs) deployed along a straight line

1. power transmission line
2. water/oil/gas pipe
3. river/coast
4. road
5. …



Energy consumption problem of UAVs

- Key issues: limited energy supply on board.
- Flight power 1000 times communication power



We focus on flight energy

- Related flight energy consumption models

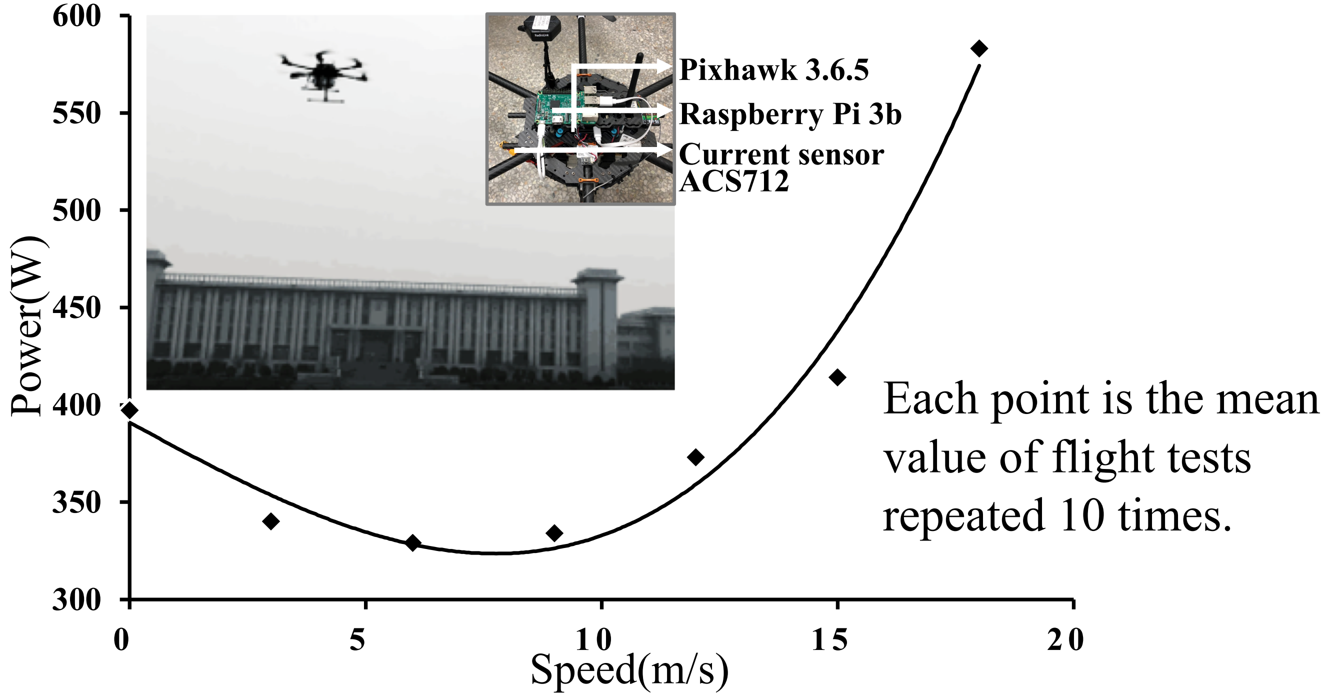
distance-related energy model

duration-related energy model

Too simple to be accurate

Our practical flight energy model

- We conduct a set of real-world flight tests



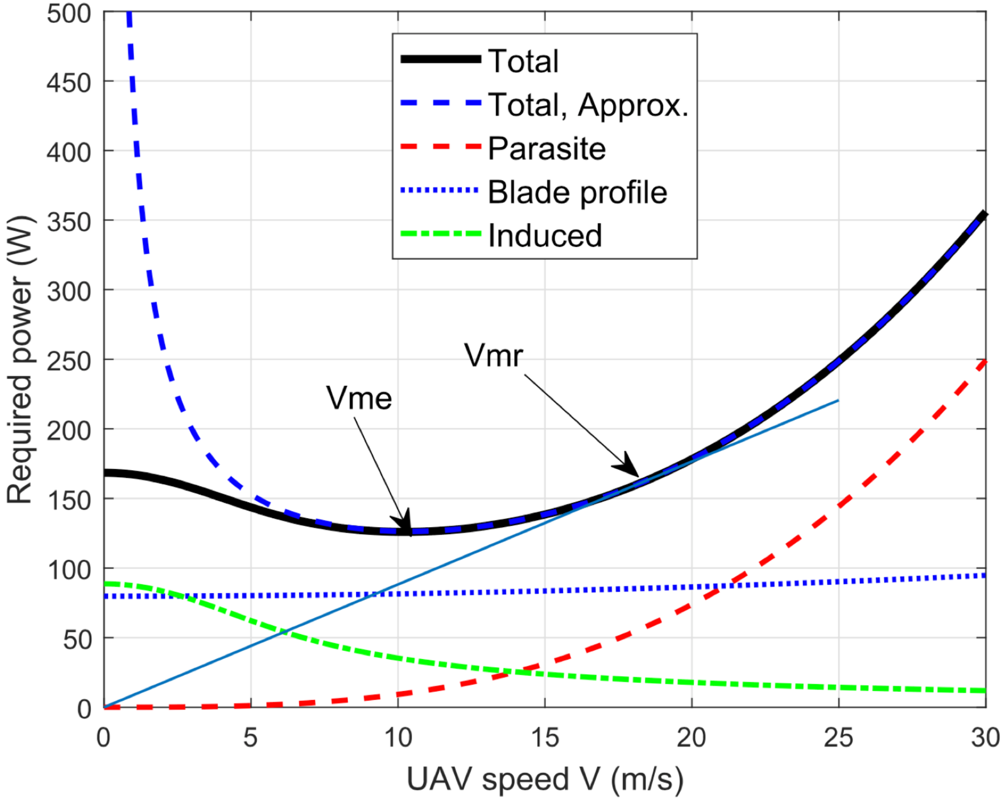
- The flight power is a convex function of the flight speed

Consistent with theoretical analysis

- Consistent with a most recent theoretical analysis.

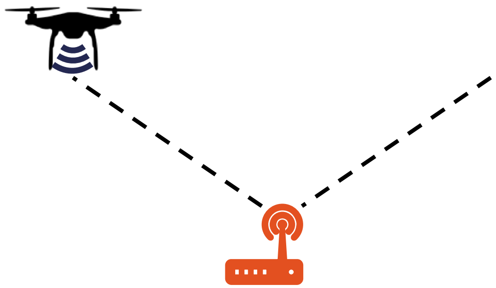
$$P(V) = \underbrace{P_0\left(1+\frac{3V^2}{U_{\text{tip}}^2}\right)}_{\text{blade profile}} + \underbrace{P_i\left(\sqrt{1+\frac{V^4}{4v_0^4}}-\frac{V^2}{2v_0^2}\right)^{1/2}}_{\text{induced}} + \underbrace{\frac{1}{2}d_0\rho s A V^3}_{\text{parasite}},$$

Y. Zeng, J. Xu, and R. Zhang, "Energy minimization for wireless communication with rotary-wing UAV," *IEEE Transactions on Wireless Communications*, vol. 18, no. 4, pp. 2329–2345, 2019.



Challenges to our problem

1. min UAV flight energy to collection all data



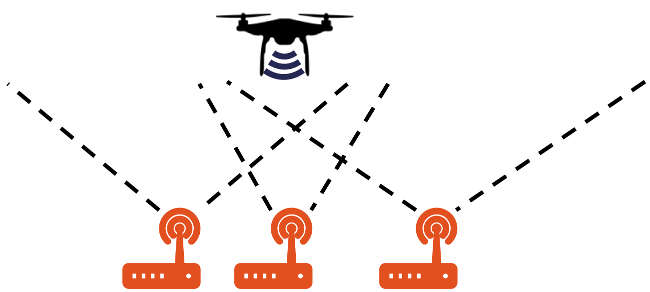
Slow speed {
- Sufficient time to collect data
- Cost more flight energy

Faster speed {
- Less time to collect data
- Save more flight energy

Best trade-off must be found

2. GNs compete for UAV time to upload data

Three GNs compete to upload their own data



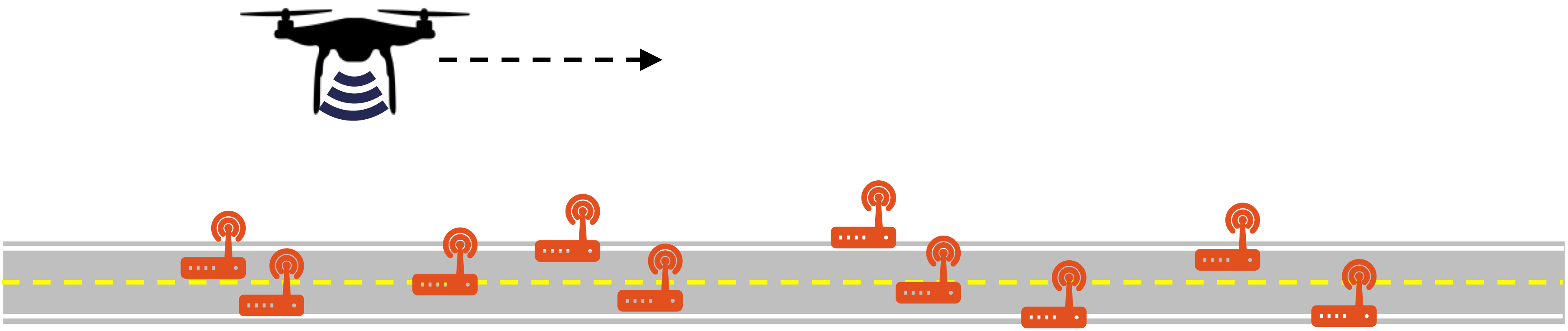
Such competition is complicated: each GN has
1. a different amount of data
2. a different transmission range size

Best GN transmission scheduling must be found

Outline

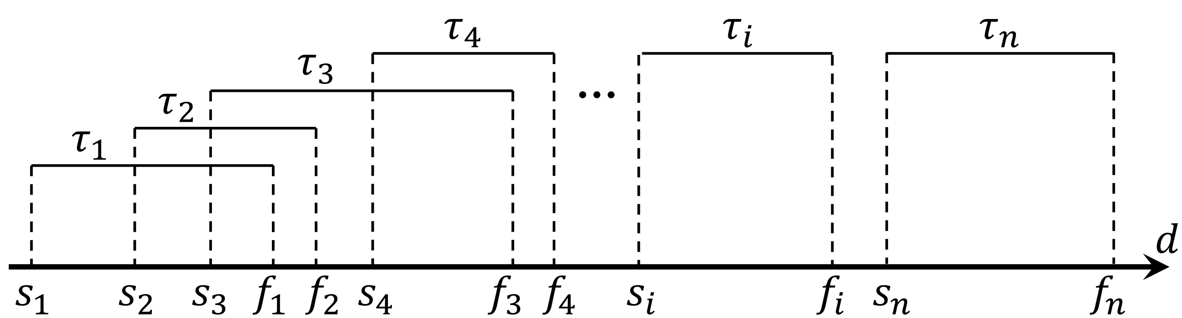
GNs and UAV

- m Ground Nodes (GNs) are deployed alone a line
- The UAV flies straightly at a fixed height
- The UAV collects data from GN when flying



Transmission range and required time

- GN i has a transmission range (s_i, f_i)
- Within range, GN i requires τ_i time to upload data
- We allow the ranges be different but aligned
  - $0 = s_1 < s_2 < \cdots < s_n$
  - $0 < f_1 < f_2 < \cdots < f_n = D$



UAV speed scheduling

- Speed scheduling function $v(t)$
  - The speed at time t
- Position of the UAV at time t

$$d(t) = \int_0^t v(\tau)\mathrm{d}\tau$$

Range/completion constraint

- Transmission ranges are overlapped but aligned, so the UAV collects data following GN index.
- At switching time t_i: the UAV finishes collecting data from GN i and starts GN $i + 1$
- Range constraint

$$s_i \leq d(t_{i-1}) < d(t_i) \leq f_i$$

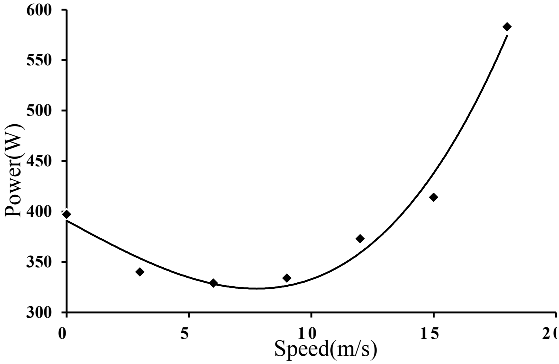
- Completion constraint

$$t_i - t_{i-1} \geq \tau_i$$

USS-GTS problem

- Flight power $p(v)$ for UAV flight speed v
- The energy consumption of UAV

$$E = \int_{t_0}^{t_n} p(v(t))\mathrm{d}t$$

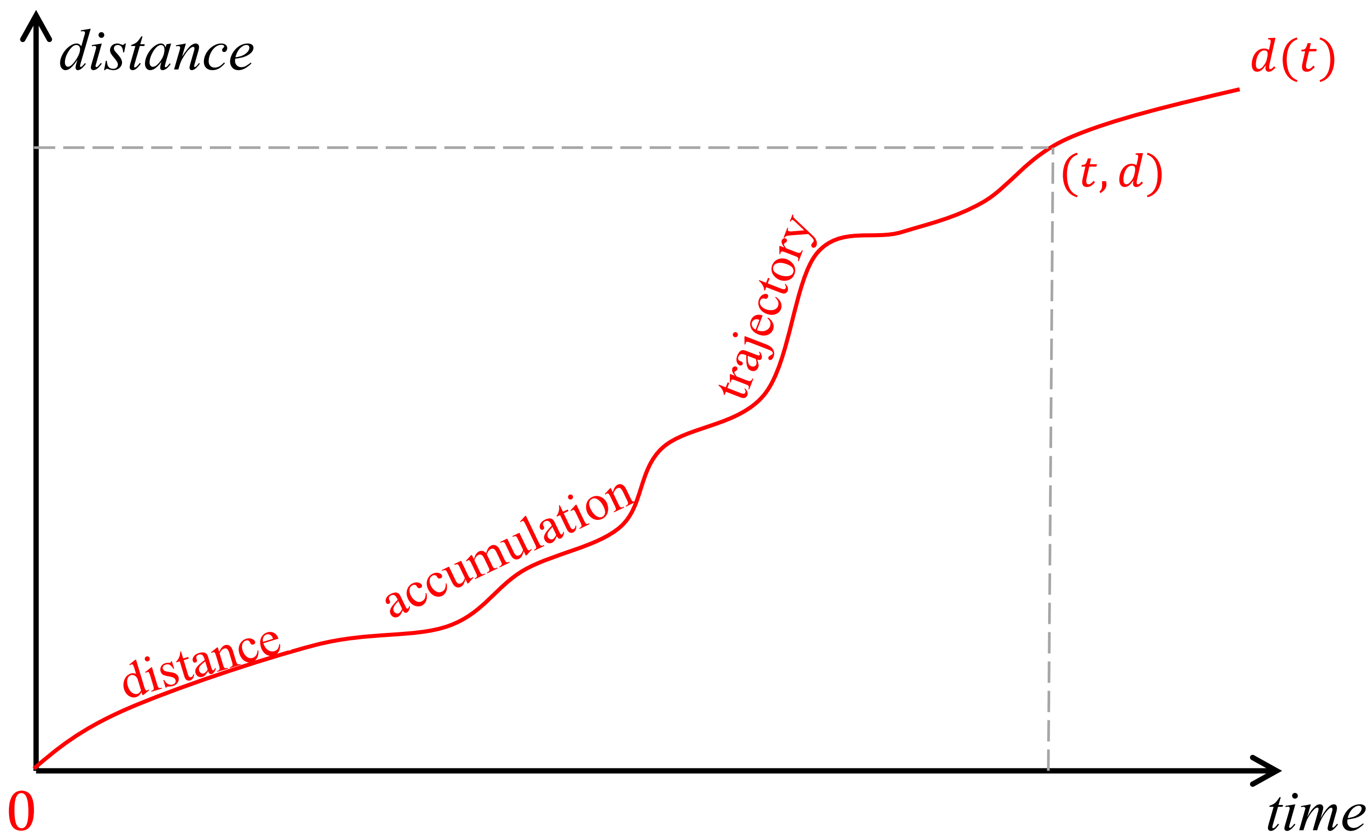


- USS-GTS problem: find speed scheduling function $v(t)$ to
  1. minimize UAV energy consumption E
  2. satisfy range constraint
  3. satisfy completion constraint

Outline

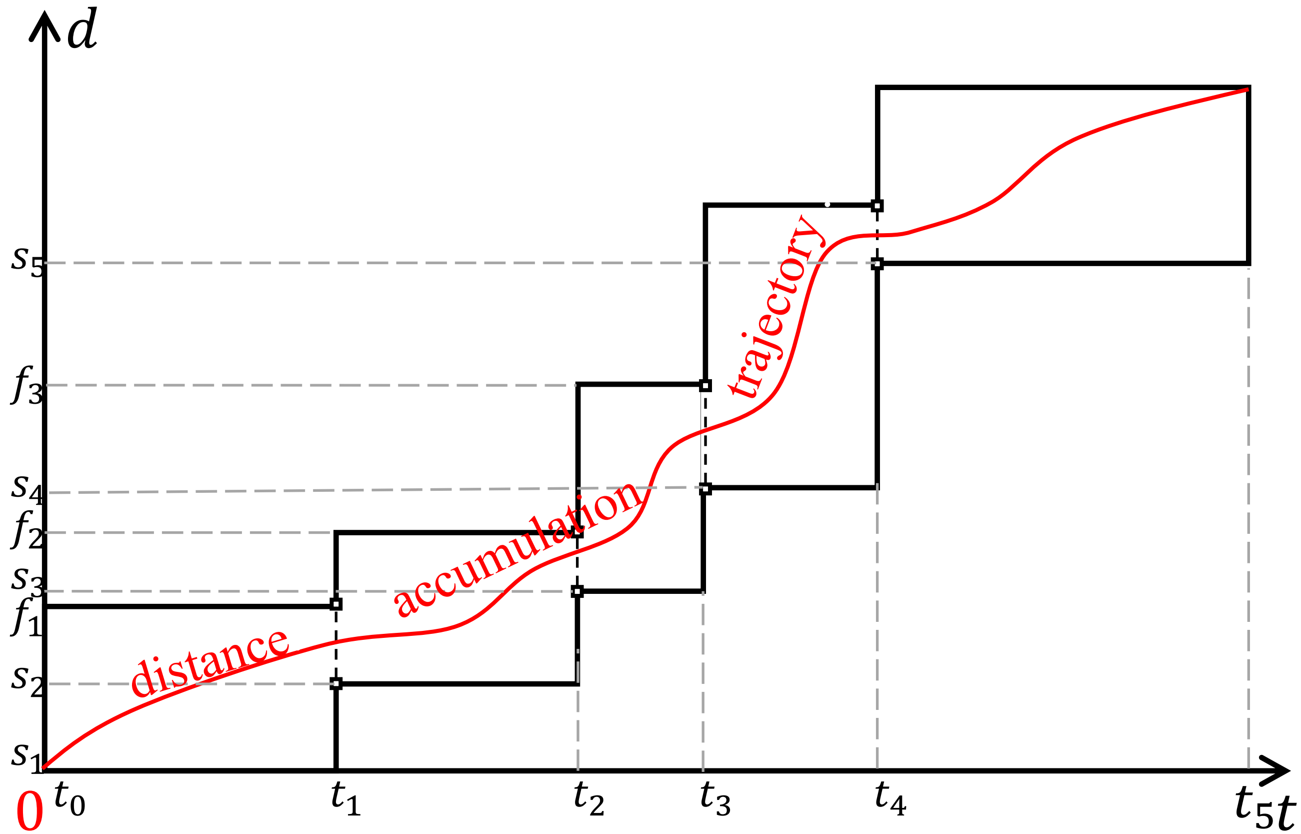
Distance accumulation trajectory

- Time-distance diagram: reaching position d at time t
- *distance accumulation function* $d(t)$ a curve
- *speed scheduling function* $v(t)$ is the curve's slope



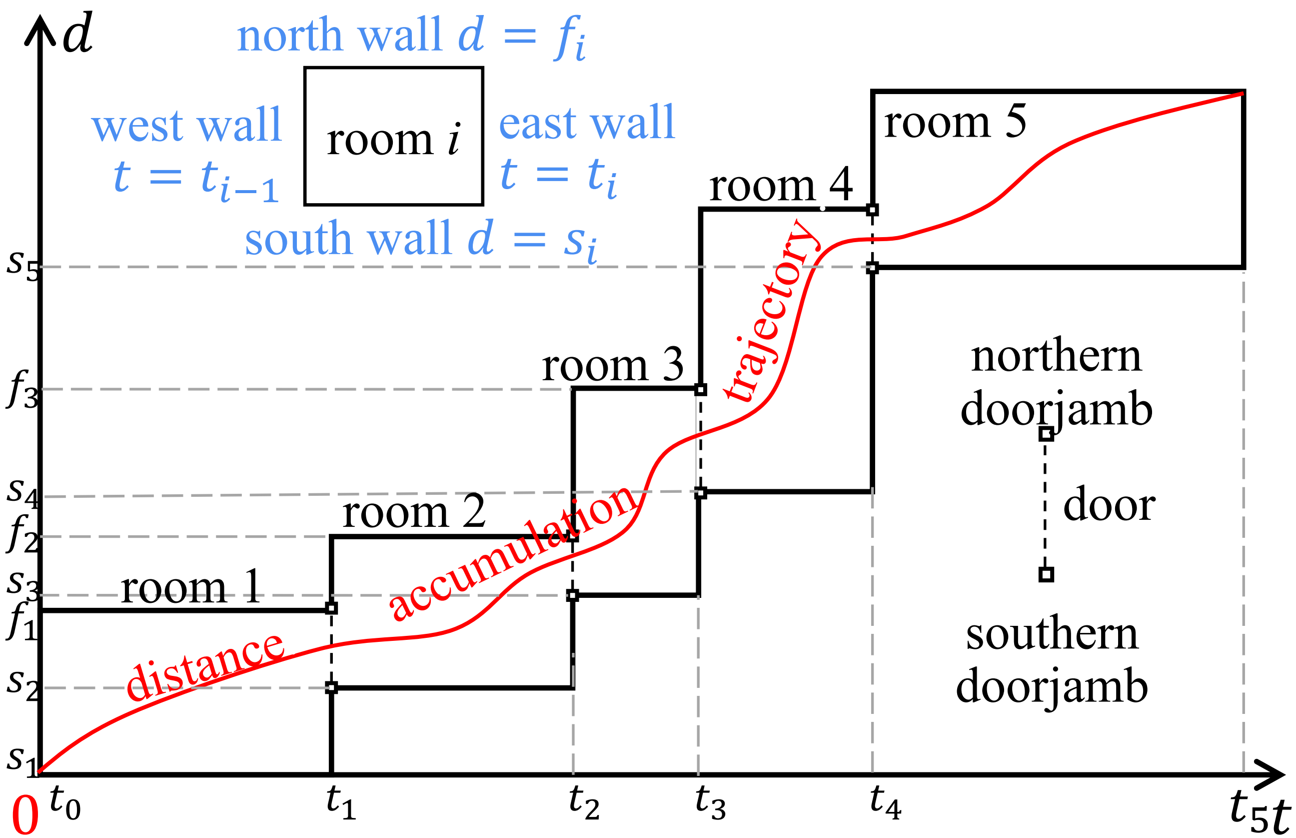
Crossing-the-Rooms problem

- Trajectory does not go freely on the diagram
- *completion constraint:* temporal on transmission times
- *range constraint:* spatial on transmission range



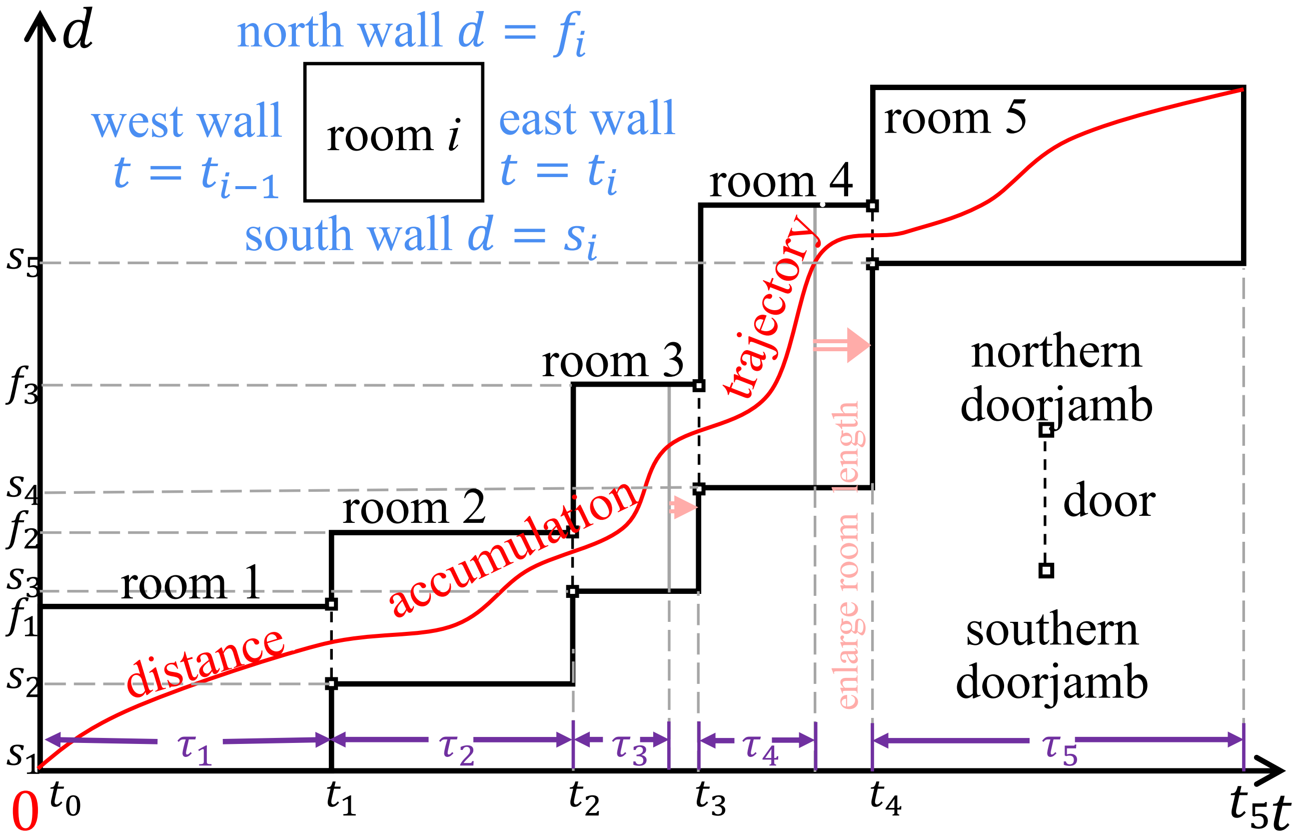
Crossing-the-Rooms problem

- For GN i, we draw a rectangle Room i: the north wall at $d = f_i$, the south wall at $d = s_i$, the west wall at $t = t_{i-1}$, the east wall at $t = t_i$



Crossing-the-Rooms problem

- *Crossing-the-rooms* problem essentially asks:
  1. how to determine the length of each room
  2. how to design the trajectory crossing all the rooms



Crossing-the-Rooms problem

- *Crossing-the-rooms* problem essentially asks:
  1. how to determine the length of each room
  2. how to design the trajectory crossing all the rooms

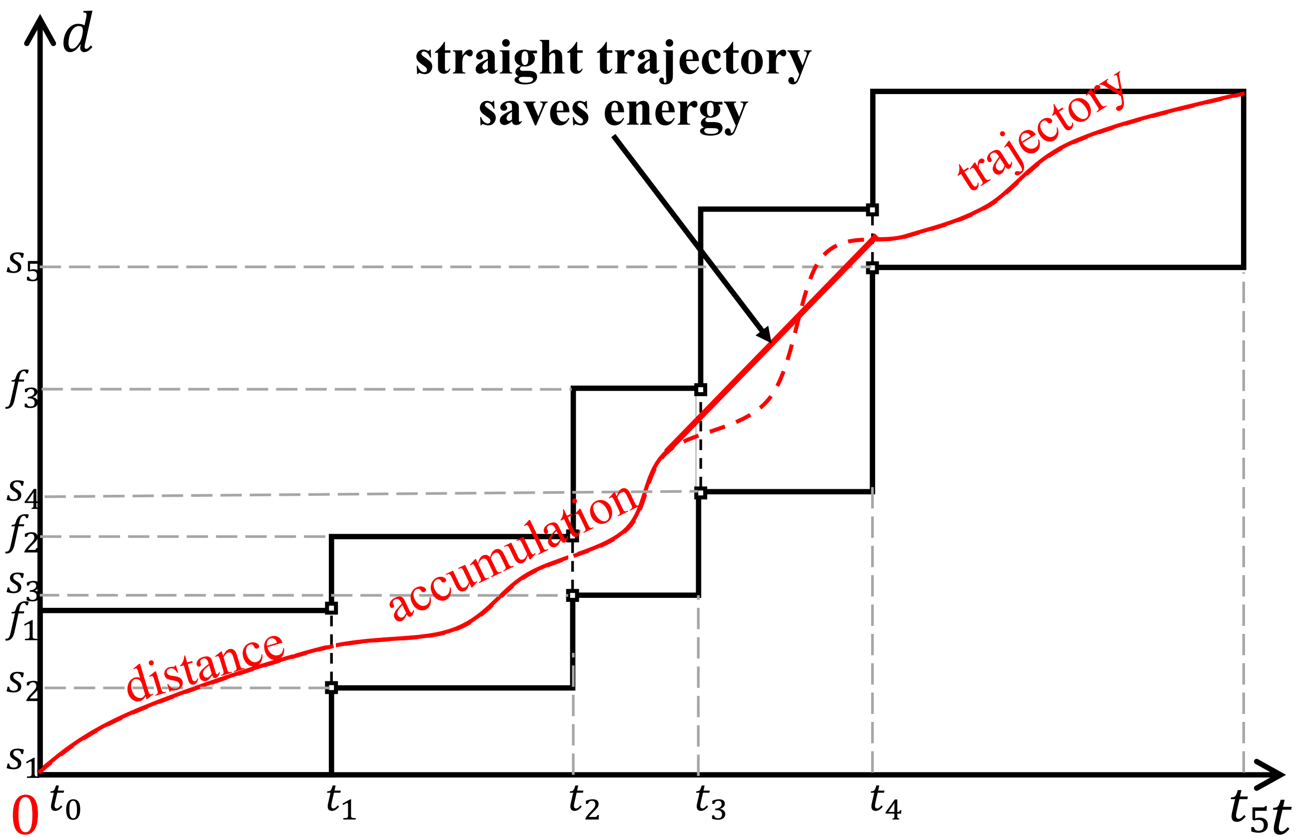
equivalent to ask the GN transmission switching times

equivalent to ask the UAV speed scheduling function

Therefore, the solution is uniquely mapped to the solution for the original USS-GTS problem.

Theorem: straight trajectory saves energy

- **Theorem**. *The optimal trajectory is straight between any two points, as long as this is feasible.*



The proposed algorithm

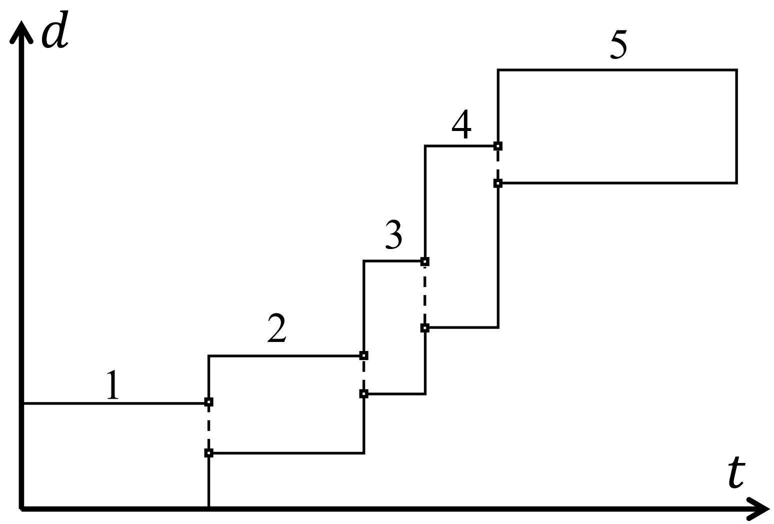
Algorithm 2: USS-GTS-General

$k = 0, d = 0, t_0 = 0$;
$s_{n+1} = f_n$ `// dummy for loop purpose`
while $k < n$ **do**
  $v_n^v = \infty$, $v_s^v = 0$;
  for $j = k + 1$ **to** n **do**
    $t_j = t_{j-1} + \tau_j$, $v_n^d = (f_j - d)/(t_j - t_k)$, $v_s^d = (s_{j+1} - d)/(t_j - t_k)$;
    if $v_s^d > v_n^v$ **then**
      $v_m = v_n^v$, $k_m = k_n^v$, $d_m = f_{k_n^v}$;
      break;
    else if $v_n^d < v_s^v$ **then**
      $v_m = v_s^v$, $k_m = k_s^v$, $d_m = s_{k_s^v+1}$;
      break;
    end
    if $v_n^v > v_n^d$ **then** $v_n^v = v_n^d$, $k_n^v = j$;
    if $v_s^v < v_s^d$ **then** $v_s^v = v_s^d$, $k_s^v = j$;
  end
  if $v_n^v == v_s^v$ **then** $v_m = v_n^v$, $k_m = n$, $d_m = f_n$;
  if $v_m > v^*$ **then**
    $x = d$;
    for $i = k + 1$ **to** k_m **do**
      $t_i = \max\{(s_i - x)/v^*, \tau_i\} + t_{i-1}$;
      $x = x + (t_i - t_{i-1})v^*$;
    end
  end
  Connect (t_k, f_k) and (t_{k_m}, d_m);
  $d = d_m$, $k = k_m$;
end

Looking before crossing rooms algorithm

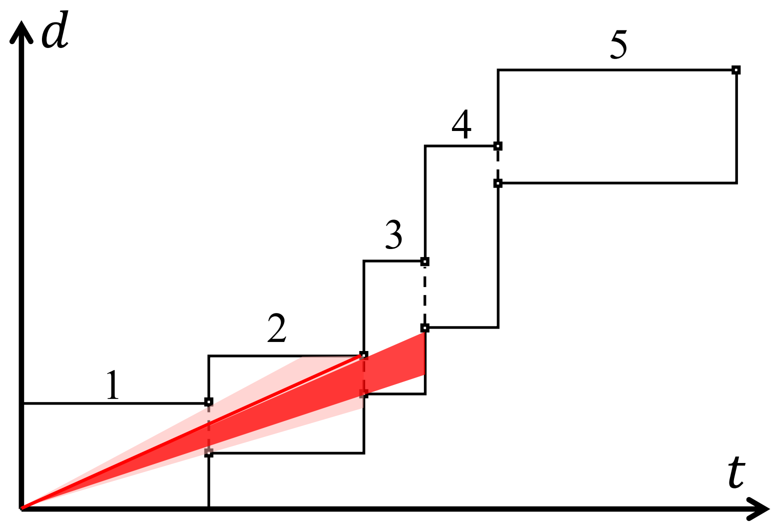
The algorithm works in three phases

1. Construct rooms
   - Room i with length τ_i, the minimal required time
2. Find a walking trajectory across rooms
3. Some room lengths are enlarged



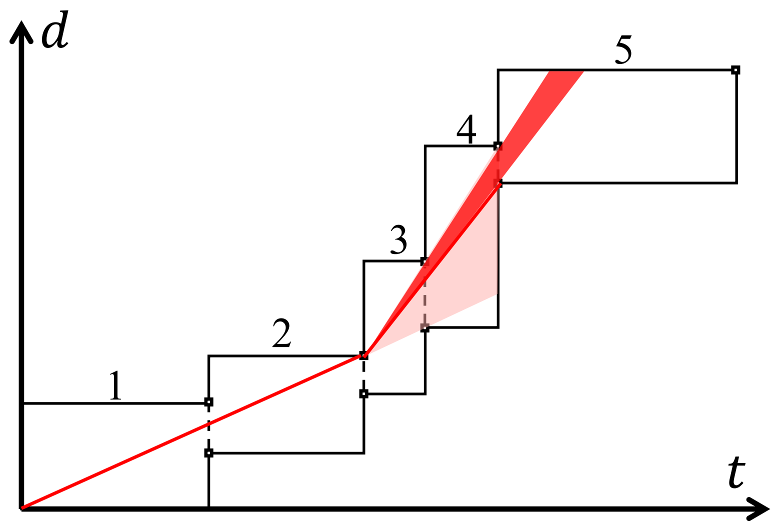
Looking before crossing rooms

- At origin, the view area through door 1 is in pink and view area through door 2 is in red.
- No view through door 3, which is beyond the northern boundary
- We walk along the northern boundary, reaching the farthest doorjamb.



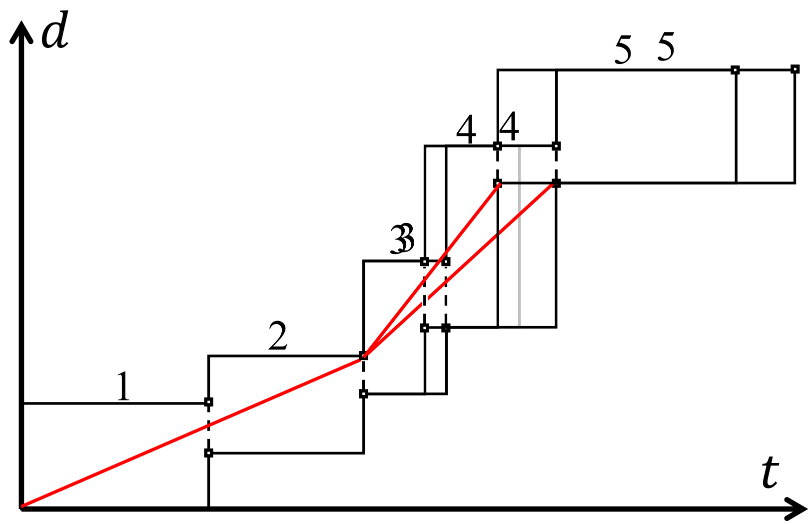
Looking before crossing rooms

- At the new position, two new view areas are in pink and red respectively.
- Since the northeast corner is beyond southern boundary of the current view area
- We walk along the southern boundary to the farthest doorjamb.



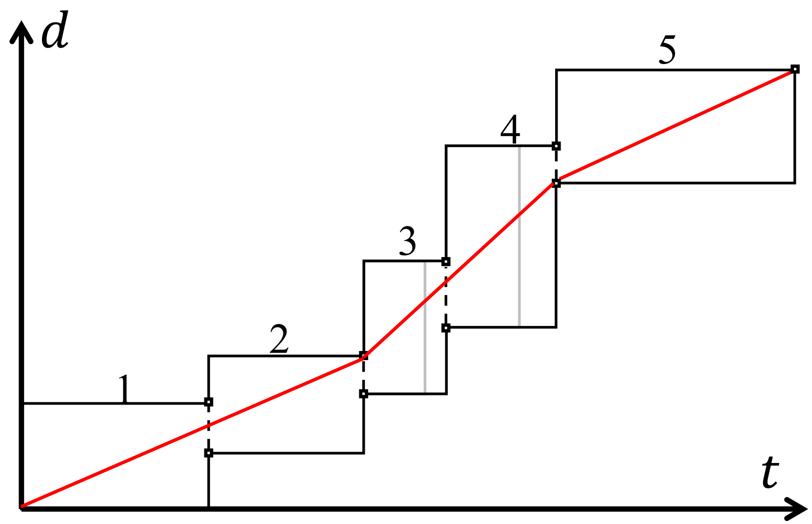
Looking before crossing rooms

- In room 3 and 4, trajectory slope larger than v^*
- **Theorem.** *Any point of the optimal trajectory has a slope no larger than* v^* .
- We enlarge the lengths of room 3 and 4 to reduce the slope to v^*



Looking before crossing rooms

- All room lengths and trajectory are determined
- **Theorem**. *Algorithm* USS-GTS-GENERAL *produces the optimal* distance accumulation trajectory *for the offline USS-GTS problem within $O(n^2)$ steps.*



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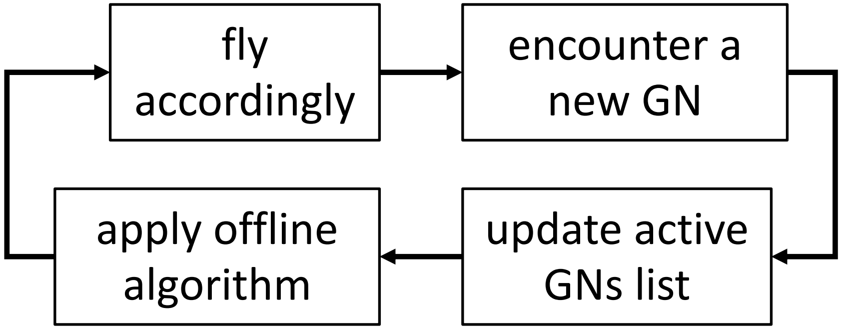
Online heuristic algorithm

- Previous offline algorithm requires all information
- In the online algorithm, we assume the information of a GN can be obtained only if the UAV flies close

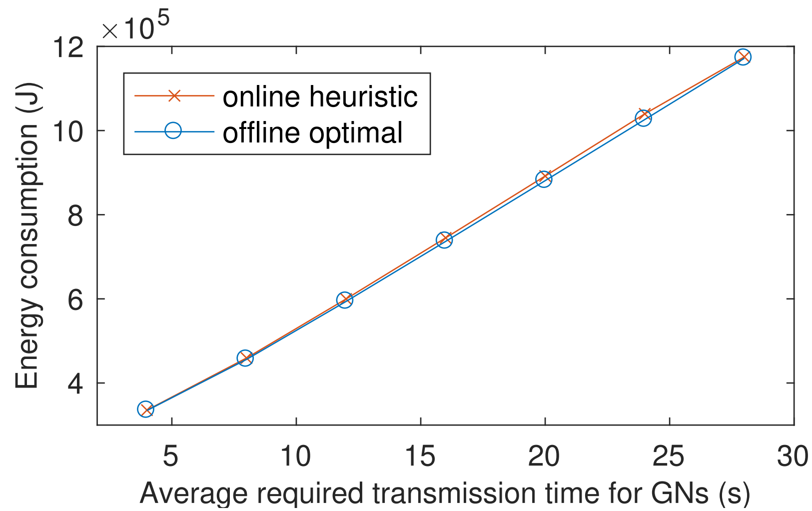
Online heuristic algorithm outline:

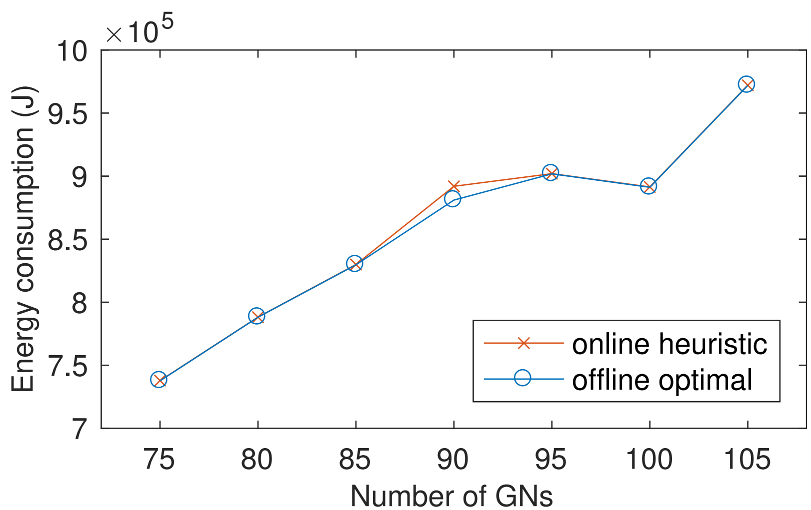


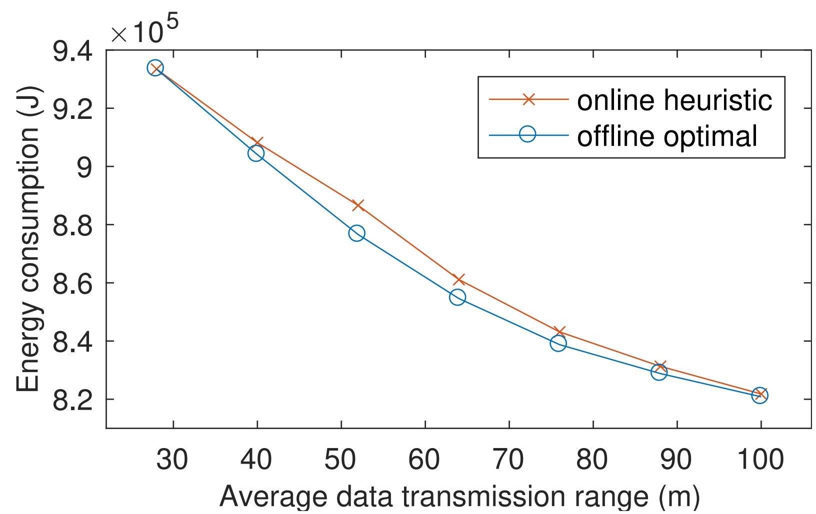
Simulation Results

- Performance comparison between online heuristic and offline optimal.

In all three settings, online heuristic performances near optimal.







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Conclusion

1. Investigate a UAV data collection problem from GNs deployed along a straight line
2. Real-world flight tests: a speed-related energy model
3. Propose the *looking before crossing* algorithm on time-distance diagram: the optimal offline solution
4. Present an online heuristic algorithm which performances near optimal.
5. Our study on the practical flight energy model and speed scheduling have shed light on a new direction on UAV-aided wireless communication.

Thank You!

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