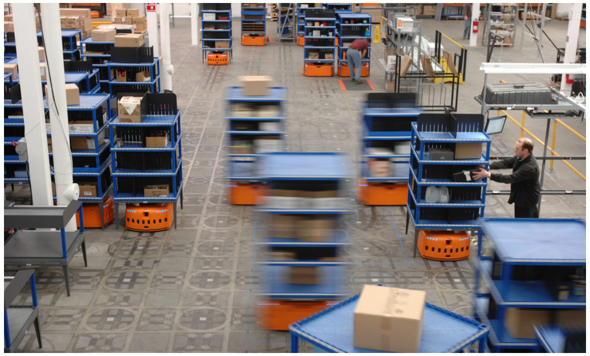
Introduction

- **Why multi-robot system?**
  - Better global system performance
  - More abilities
  - More robustness
  - Lower cost
- **What is multi-robot coordination?**

A team of robots interacting with others to reach a common goal.



Kiva Systems

Robocup

Introduction

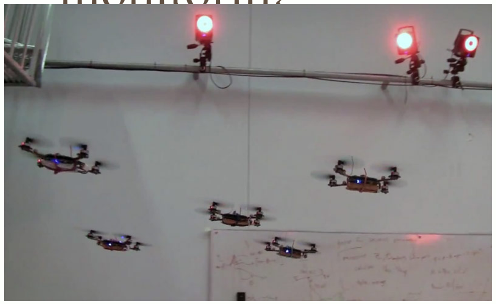
- **Why building efficient multi-robot coordination is difficult?**

Most problems are ***NP-hard***:

- Multi-robot **Task Allocation**
  - Resource allocation
  - Exploration

Wildfire monitoring

- Multi-robot **Motion Planning**
  - Routing
  - Trajectory planning



Multi-UAV path planning

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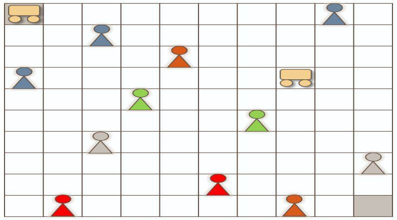
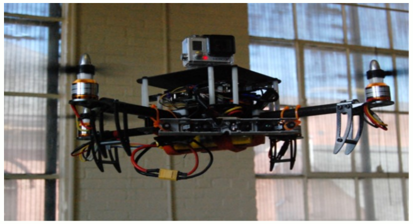
Introduction

- How to reduce the difficulty?
  - Reduce the environment space
  - Reduce the action space
  - Estimate a finite horizon of future

Outline

- Known Environment with Global Communication:
  -  Intelligent In-Orchard Bin-Managing System For Tree Fruit Harvest
  -  Multi-robot Routing for Dynamic Information Gathering
- Unknown Environment with Limited Communication:
  -  Multi-UAV Explore, Map, and Search in Unknown Environments

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Intelligent In-Orchard Bin-Managing System for Tree Fruit Harvest

(aka. the Bin-dog project)

Motivation

- High labor demand of tree fruit(apple) harvest
- Low productivity with inefficient bin management






Apple harvest in Prosser , WA.

Main Goal

To develop an intelligent bin-managing system supported by a robotic self-propelled fruit bin carrier

"Bin-dog", designed by Center for Precision & Automated Agriculture Systems, Washington State University

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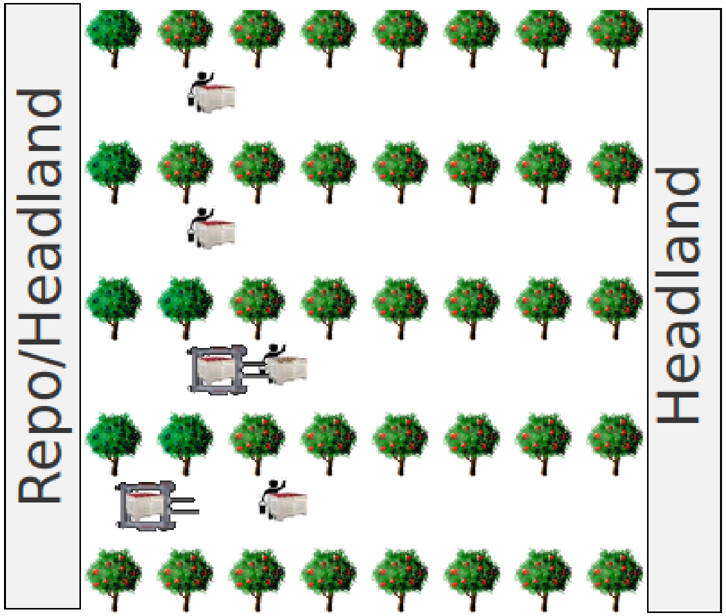
Simulation Environment

- 10 trees x 5 lanes
- Workers cost **2** steps to finish one tree
- Robots move ***1*** step per time when carrying a full bin, **2** steps otherwise.



Simulation Setup

- Groups of workers are initialized in the beginning of the lanes.
- No more apples?
  - Workers move to a new location.
  - Workers request a new bin.
- Robots choose which bin to pick up.
  - Robots wait if the target bin is not full yet.
- Robots choose where to carry a new bin to.

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Algorithm: Baseline (Naive Greedy)

- Greedy, no coordination.

- Choose the closest full bin.
- Choose the earliest requested location.

- Choose the bin that will be filled faster.
  - Wait if the target bin is not full.

- Priority: other robots cannot see a chosen bin/request.

Not efficient!

Algorithm: Auction-based

- Robots coordinate through auction.
  - Each robot makes plans to pick up a bin.

- Plan cost:

$$C = t_T + t_W$$

  - t_T: the time required to reach target bin.
  - t_W: the time required to wait for target bin to be full.

- The one with least cost wins the task

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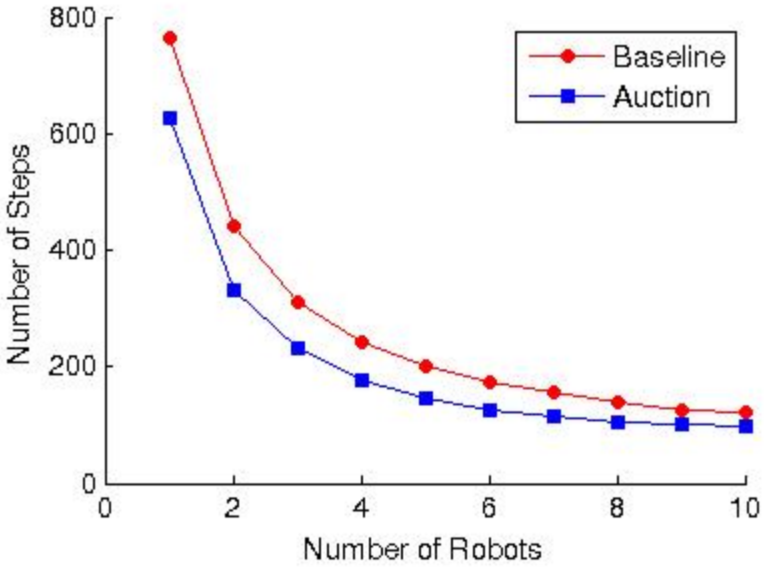
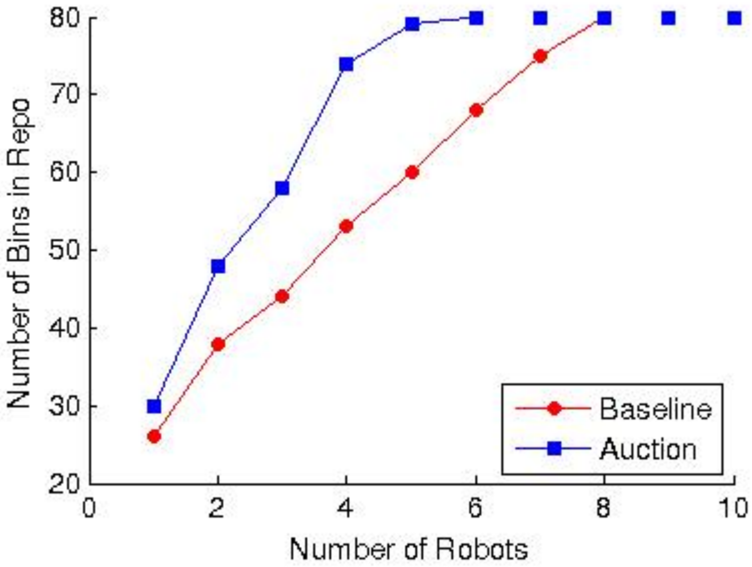
Simulation (Auction-based)

Results

Total steps cost to finish all the tasks (80 bins)



Number of bins retrieved after 150 time steps



Lower is better

Higher is better

Extension

"Bin-dog" is interesting, but...

- Visit multiple points of interest one time?
- How to balance the workload between robots?
- Workers work in different speed?

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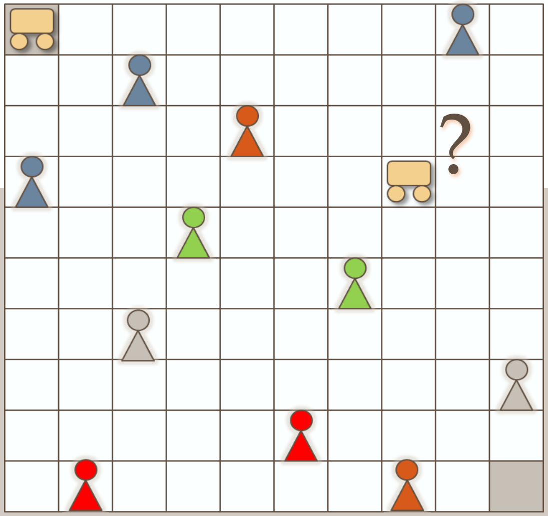
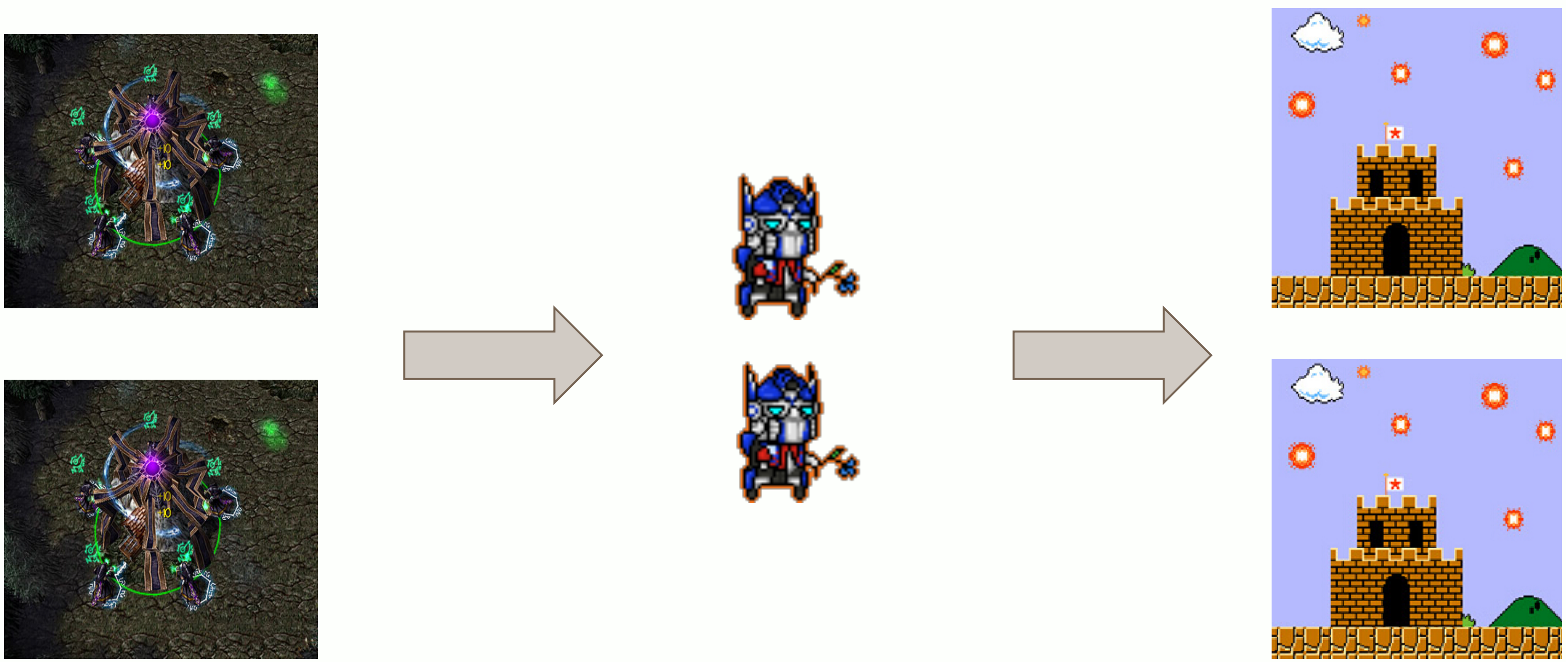
Multi-Robot Routing for Information Gathering



Introduction

Goal

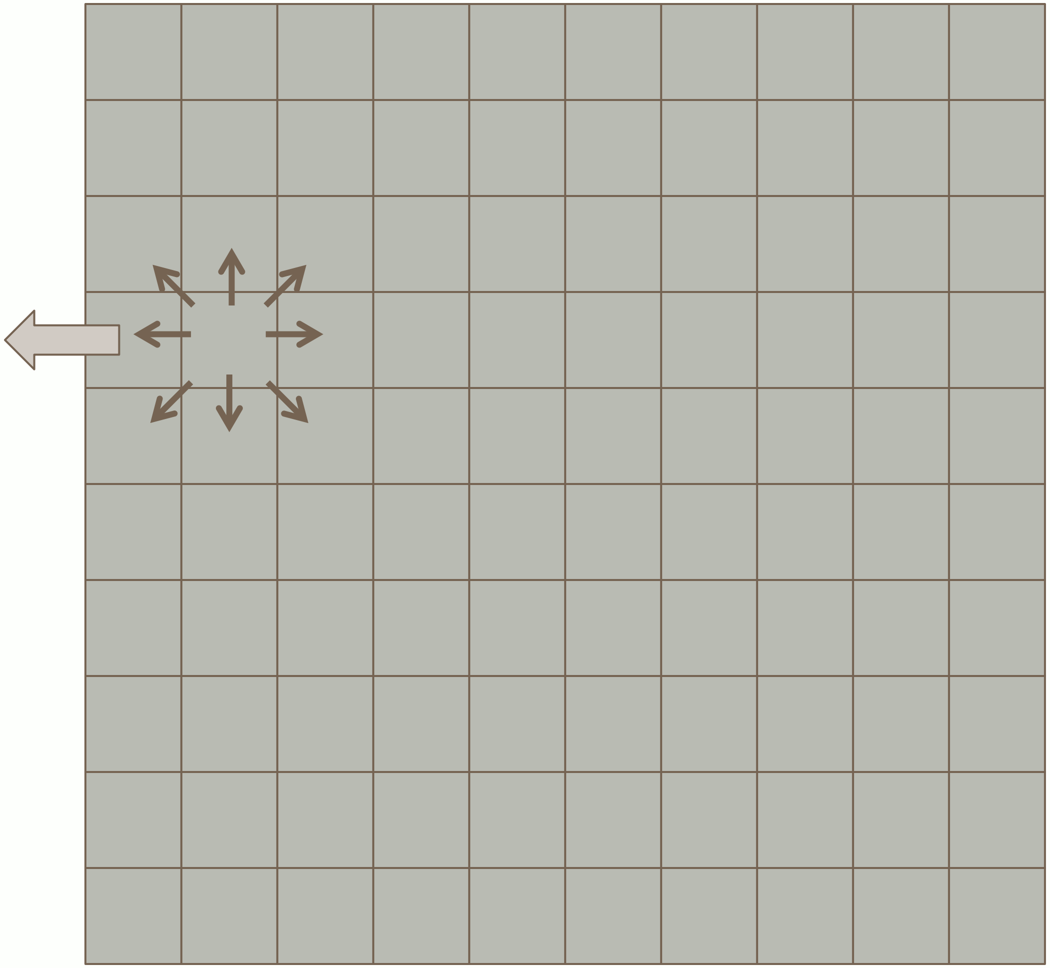
Coordinate a team of robot to retrieve resources from a number of resource collectors in a static environment.



Introduction

Informative map

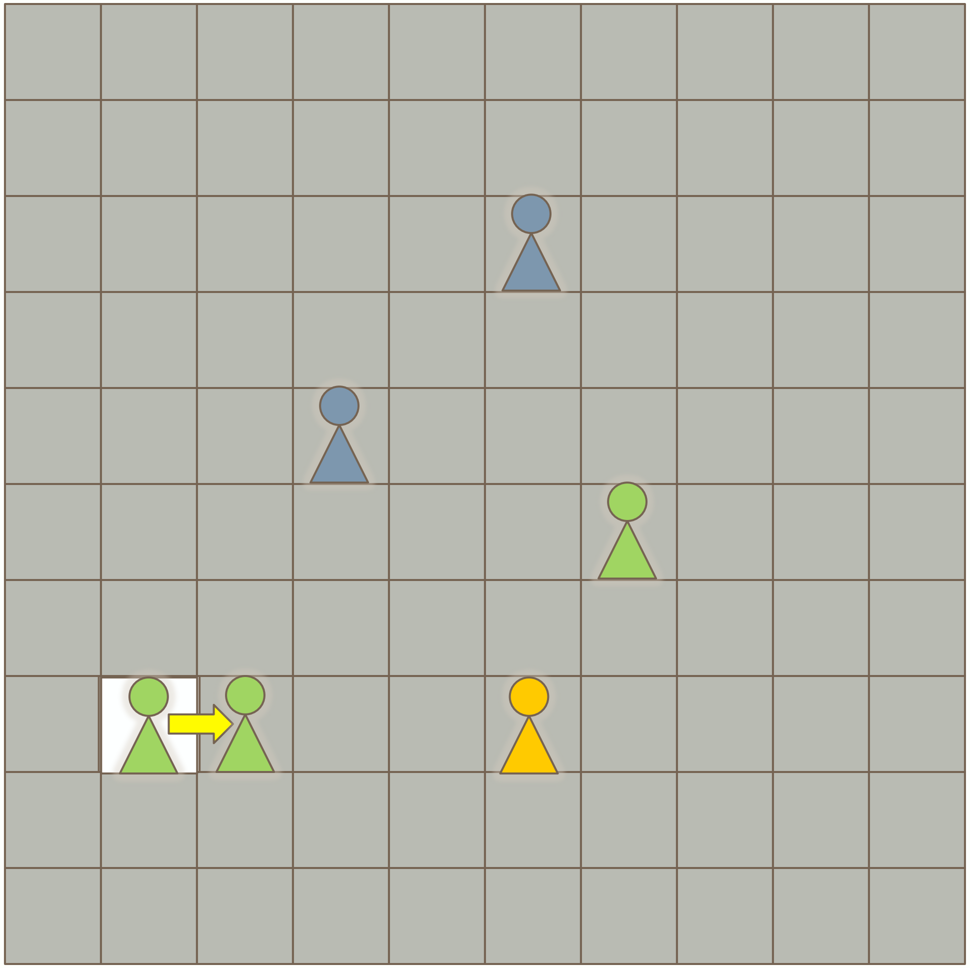
- **8-connected 2D grid**
- **No obstacles**
- **Each cell has a certain amount of information**



Introduction

Collectors:

- Collect information from each cell
- Move to a neighbor cell when finish
- Individual collecting rate
- Limited capacity, pause when full



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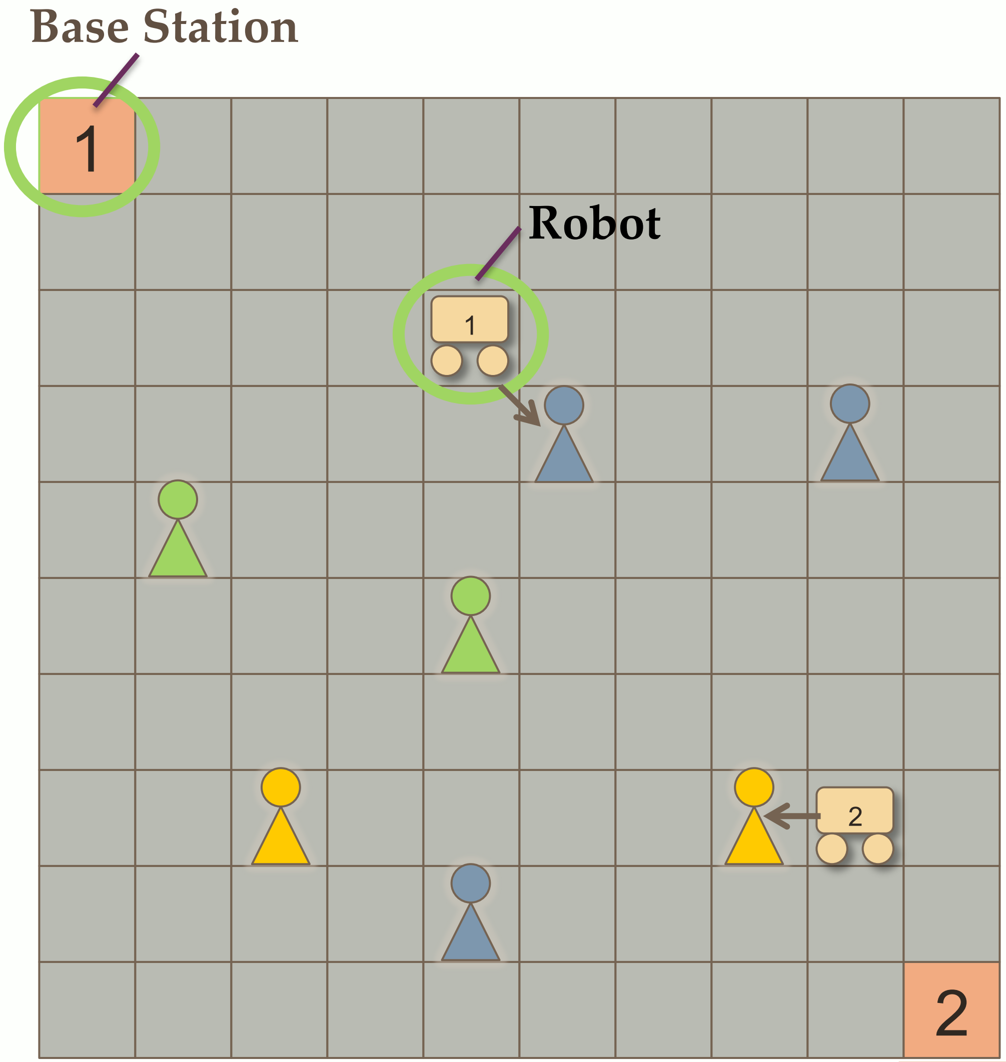
Introduction

Robots

- **Visit collectors to retrieve information**
- **Consistent speed**
- **Different base stations**
- **Limited capacity, go back if full**

Robot can retrieve **a portion** of information from each collector



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Problem Formulation

- **Given:**
  - **n collectors**
  - **m robots**

- **Objective Function**

$$argmax(\sum_{p_i \in \Psi} Info(R_{i...m}) - Idle(T_{i...n}))$$

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Sub-problems

- Two sub-problems
  - Multi-robot Task allocation:
    - which collector should be assigned to which robot?
  - Multi-robot Motion Planning:
    - Visit the goal collectors in which order?
    - Retrieve how much information from a specific collector?

Algorithm: Sequential Auction with Greedy Path Planning

- **Task Allocation**: Sequential Auction
  - Sort the unassigned tasks (collectors) by *urgency:*

    U_i = (collecting rate + current fullness)/distance

  - Auction tasks based on urgency
  - Cost of each robot:

    c_i = total travel distance of current tasks + distance from last task to the auctioning task

  - Reassign if any robot idle

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Demo: Sequential Auction with Greedy Path Planning

Be *exact* full after visit all assigned collectors

$U_1 > U_2$

$T = 11$

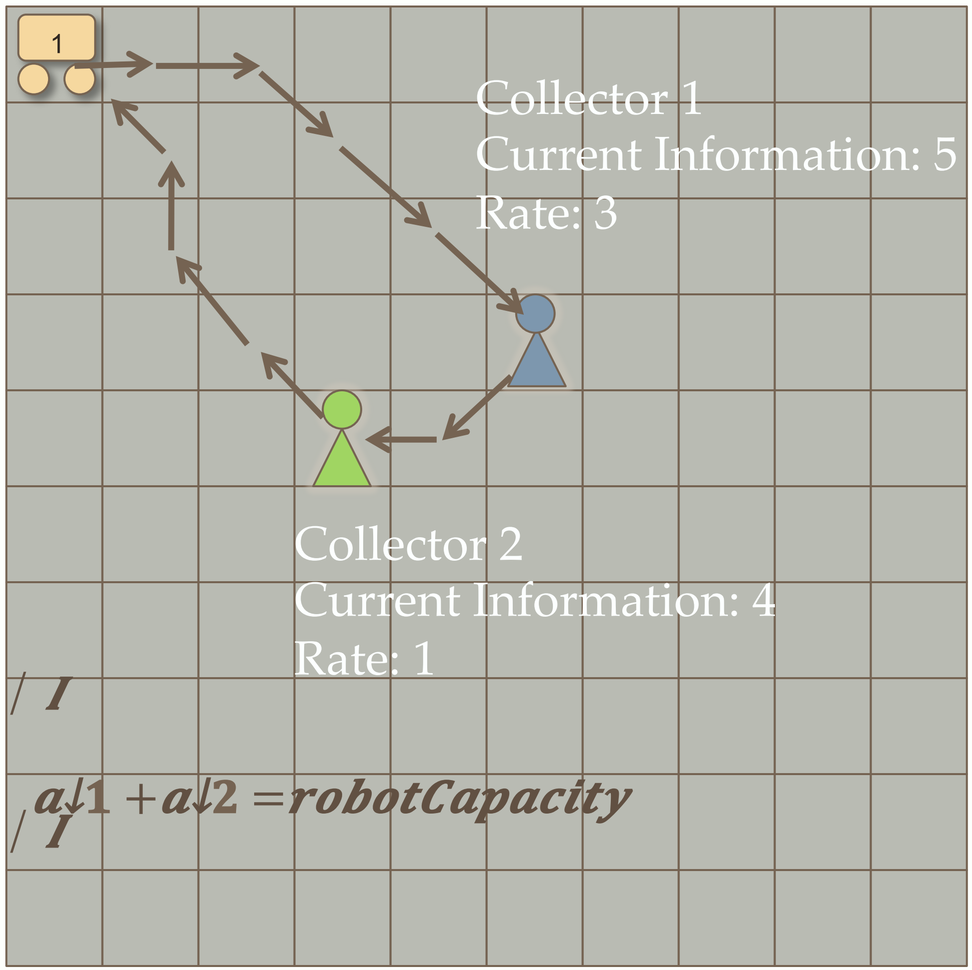
Information Collected Estimation:

$I = (r_1 + r_2) * T + CUR$

Information Retrieve for collector 1:

$a_1 = (r_1 * T + cur_1) / I * \text{robotCapacity}$

$a_2 = (r_2 * T + cur_1) / I * \text{robotCapacity}$



$a_1 + a_2 = robotCapacity$

Algorithm: Sequential Auction with Greedy Path Planning

- **Motion Planning:** Greedy
  - **Path Planning :** 1-horizon greedy. Visit the most urgent collector first.
  - **Information Gathering Planning**
    - T : time *required* to travel the path.
    - Estimated information collected by collector *i*:

$$\Delta_i = content_i + T \times f_i$$

    - Amount to take (Try to be ***exact*** full after visit all assigned collectors):

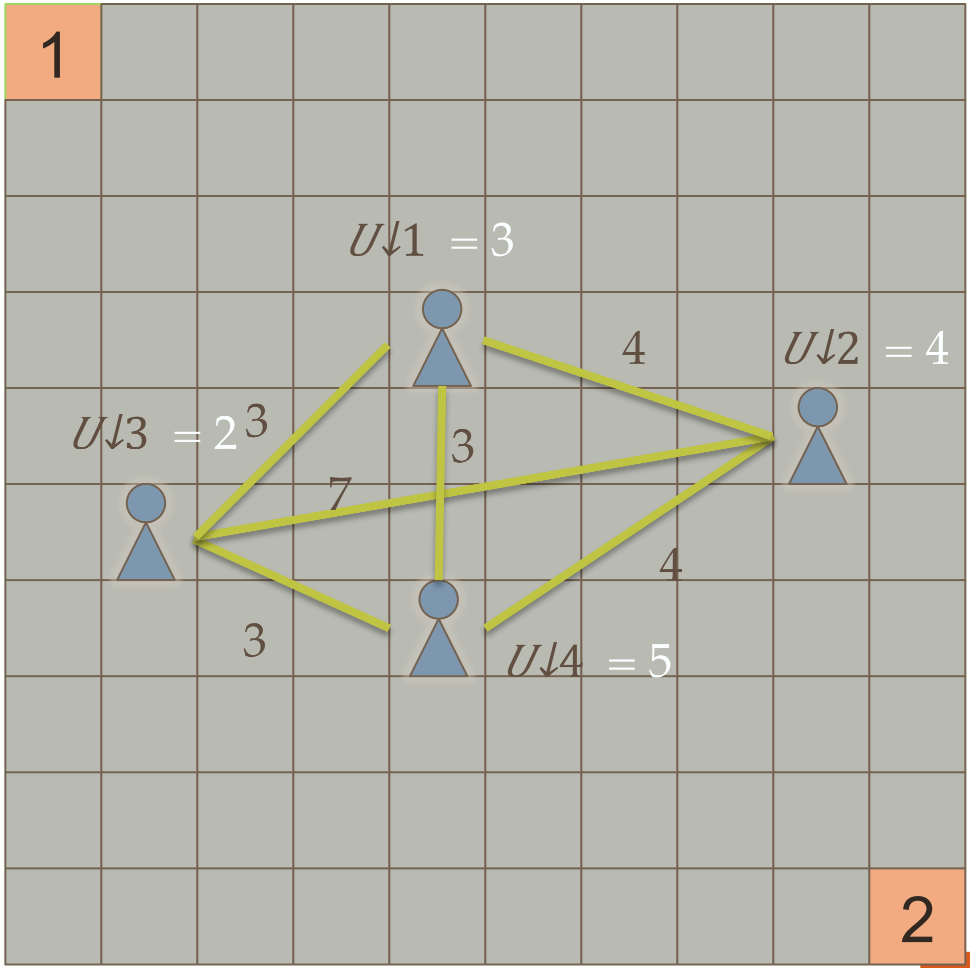
$$a_i = \Delta_i / \sum_{j=1}^{|P|} \Delta_j \times RobotCapacity$$

Algorithm: Distributed Sampling with RH-based Path Planning

- **Task allocation**: distributed sampling.
  - **Goal**: evenly distribute the workload to the robots

Demo:
Distributed Sampling with RH-based Path Planning

Create fully connected Graph G



algorithm modified from (Kim and Shell,2014)

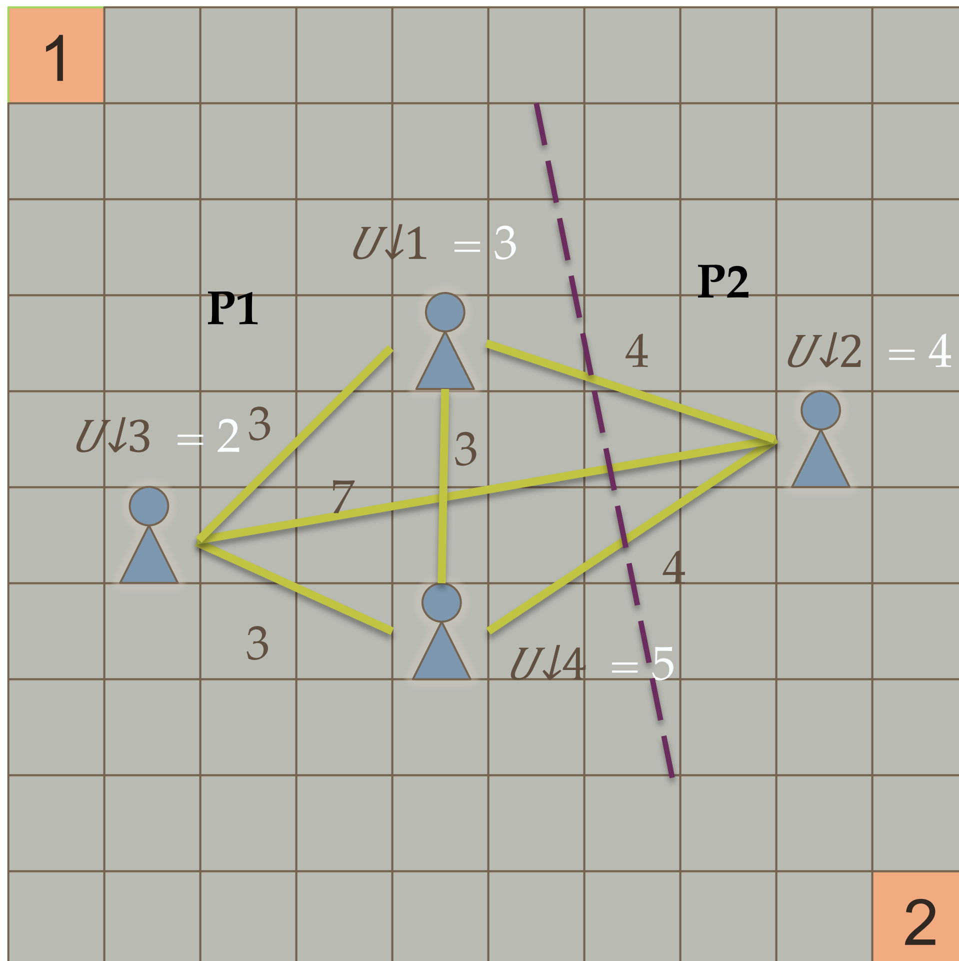
Demo:
Distributed Sampling with RH-based Path Planning

Random part it into *m* parts.

$\text{Cost}(P1) = \text{sum}(U_{1,3,4}) + \text{sum}(E_{13,14,34}) = 19$

$\text{Cost}(P2) = 4$

$\text{Diff}(P1, P2) = 15$



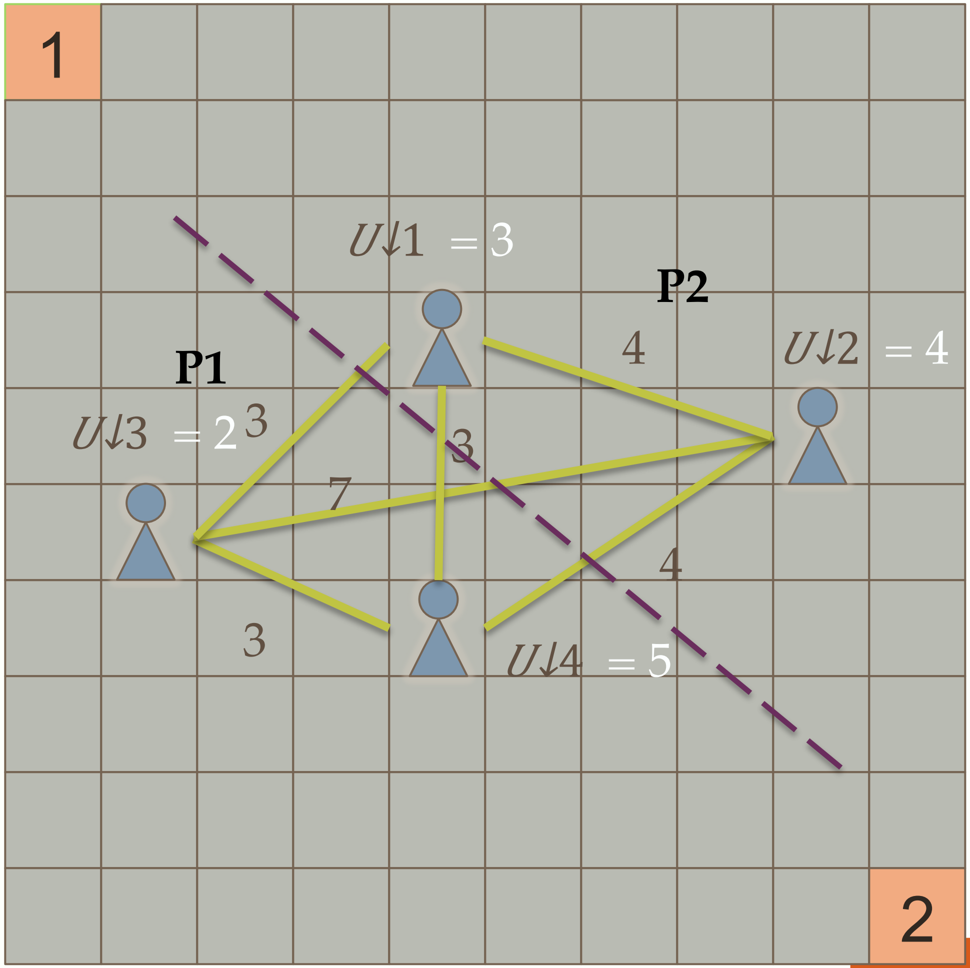
Demo:
Distributed Sampling with RH-based Path Planning

Balance by move the boundary nodes.

Cost(P1) = 10
Cost(P2) = 9

Diff（P1, P2）= 1 < previous Diff15

A better partition!



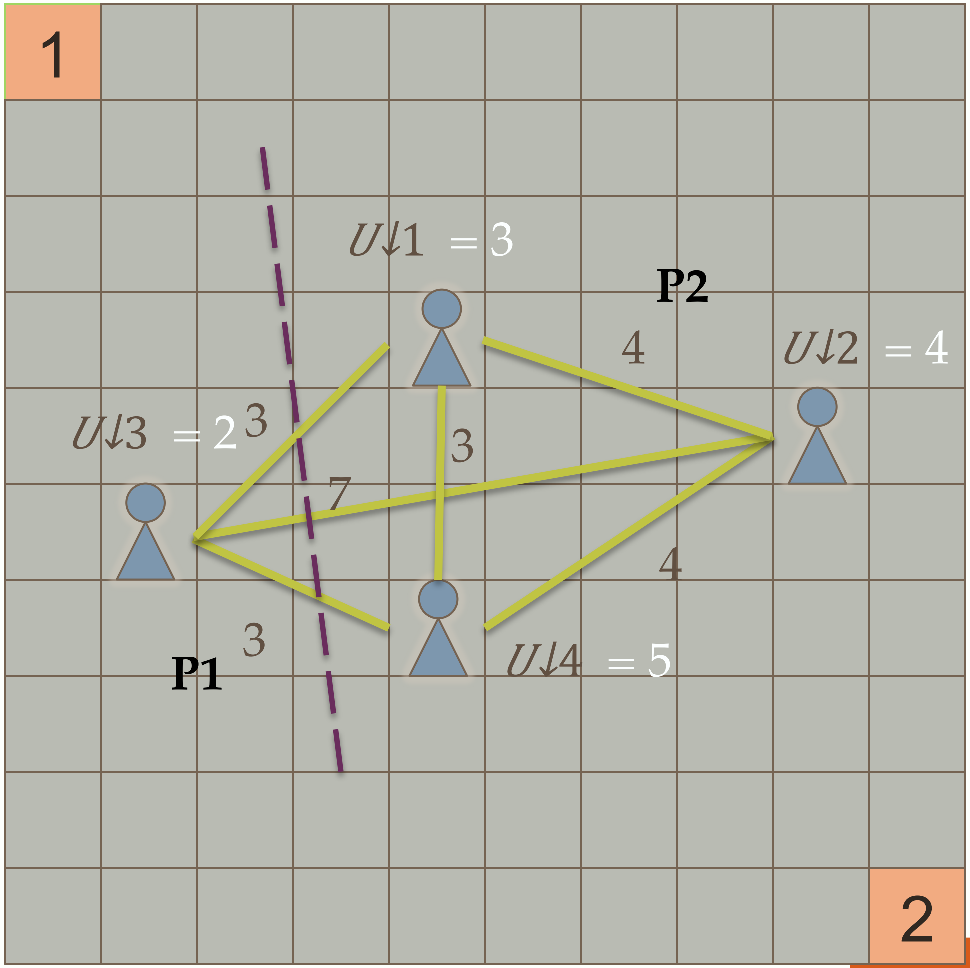
Demo:
Distributed Sampling with RH-based Path Planning

Balance by move the boundary nodes.

Cost(P1) = 2
Cost(P2) = 23

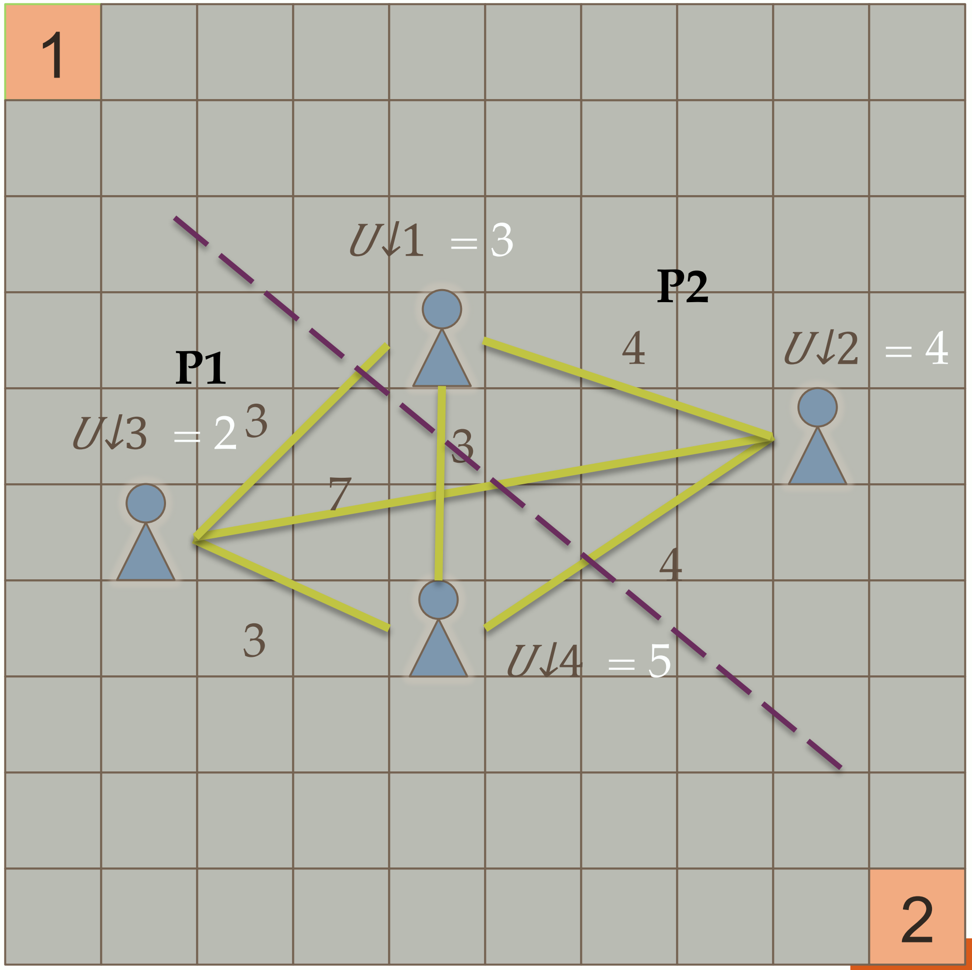
Diff（P1, P2）= 21 > 1

↑
previous Diff



Demo:
Distributed Sampling with RH-based Path Planning

Continue until converged



Workload Partition

Steps:

- Create a fully connected graph $G = (V, E)$
- V is the set of all nodes (collectors), E is the set of edges.
- Optimization problem:

$$\arg \min_{(G_i, G_j)} \left[\max_{i \in [1,m]} \left(\sum_{\forall a,b} (w^i_{v_a} + w^i_{e_b}) \right) - \min_{j \in [1,m]} \left(\sum_{\forall c,d} (w^j_{v_c} + w^j_{e_d}) \right) \right].$$

Time required to reach capacity

Collector's fill rate

$$w_{v_a} = -t_{v_a} + f_{v_a}$$

$$w_{e_b} = length(e_b)$$

Proposed Algorithm: Distributed Sampling with RH-based Path Planning

- **Routing**
  - Receding Horizon-based routing.
  - Look ahead h steps.

- Preferences of visiting a node v_i:

$$c_i = U_i / d_i$$

  - $d_i = dist(R, v_i)$ if v_i is the first node in the path
  - $d_i = dist(v_j, v_i)$ otherwise

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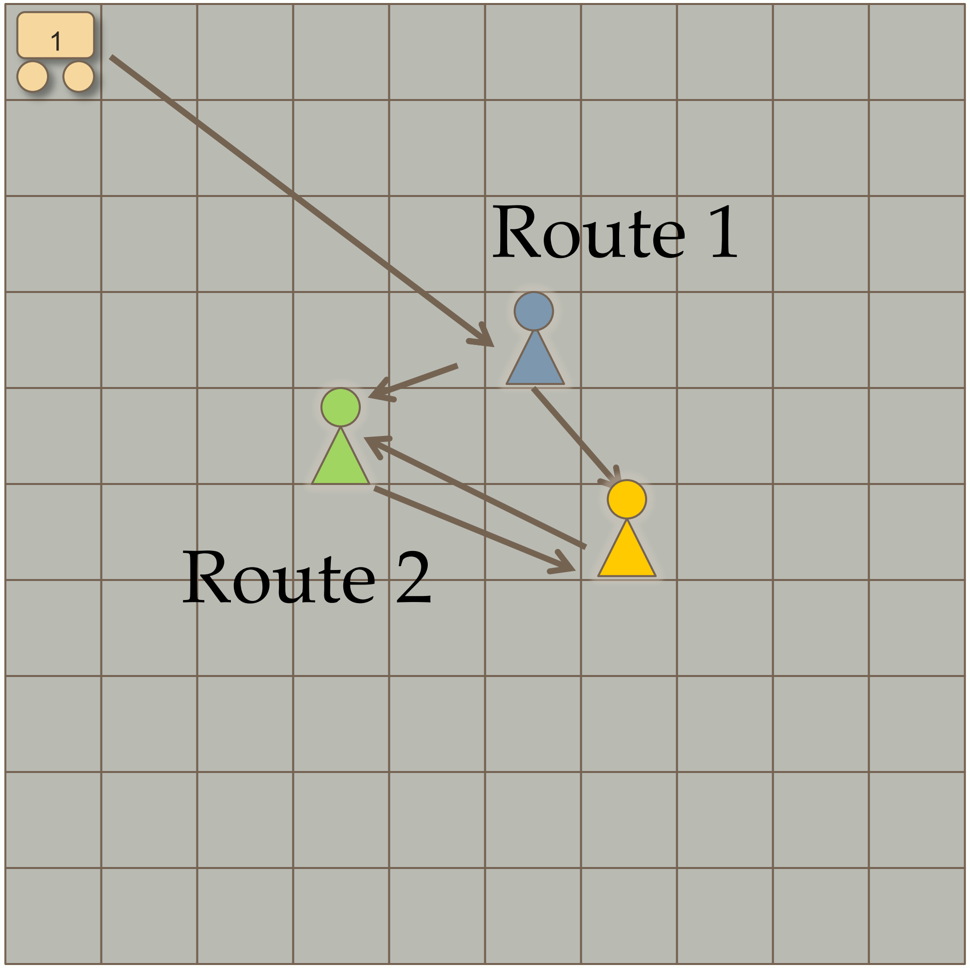
Receding Horizon Path Planning

Find which collector to visit first

3-horizon planning

Route 1
Route 2
…
Route 6



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Proposed Algorithm: Distributed Sampling with RH-based Path Planning

- Information Gathering Planning
  - T : time *required* to travel the path.
  - Estimated information collected by collector *i*:

$$\Delta_i = content_i + T \times f_i$$

  - Amount to take (Try to be ***exact*** full after visit all assigned collectors):

$$a_i = \Delta_i / \sum_{j=1}^{|P|} \Delta_j \times RobotCapacity$$

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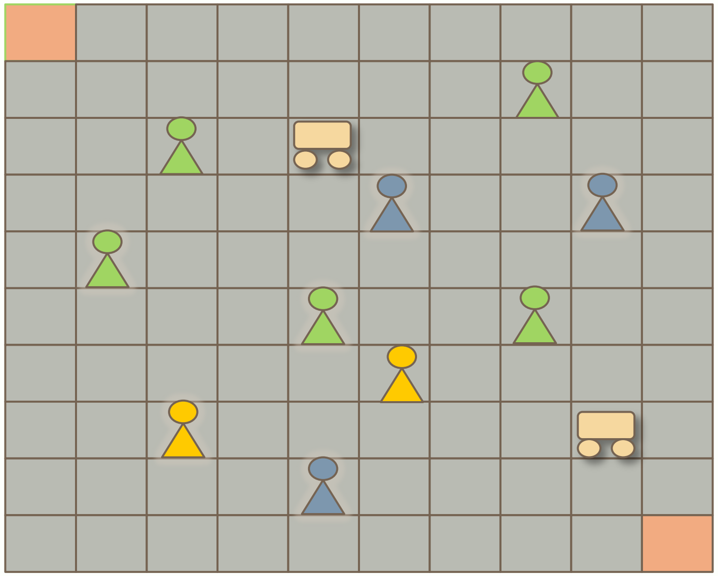
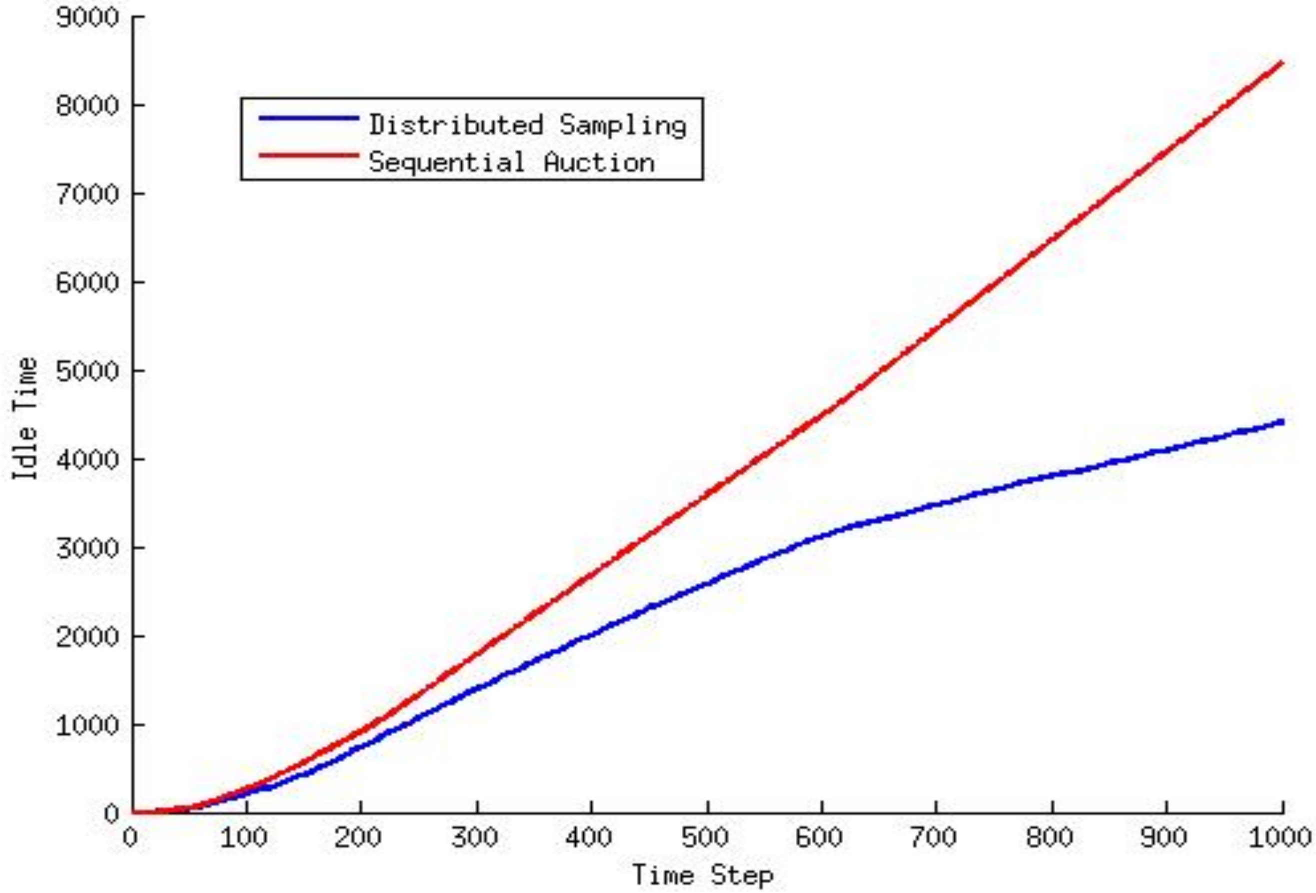
Simulation

- 10 x 10 cells. Each cell contains 200 units of information
- Collectors: 2 collectors with collecting rate 5, 3 collectors with rate 2, 5 collectors with rate 1.
- Capacity: Both robots and collectors have a capacity of 100 to store information.
- Robots start from different corners.



Idle Time (1000 steps)



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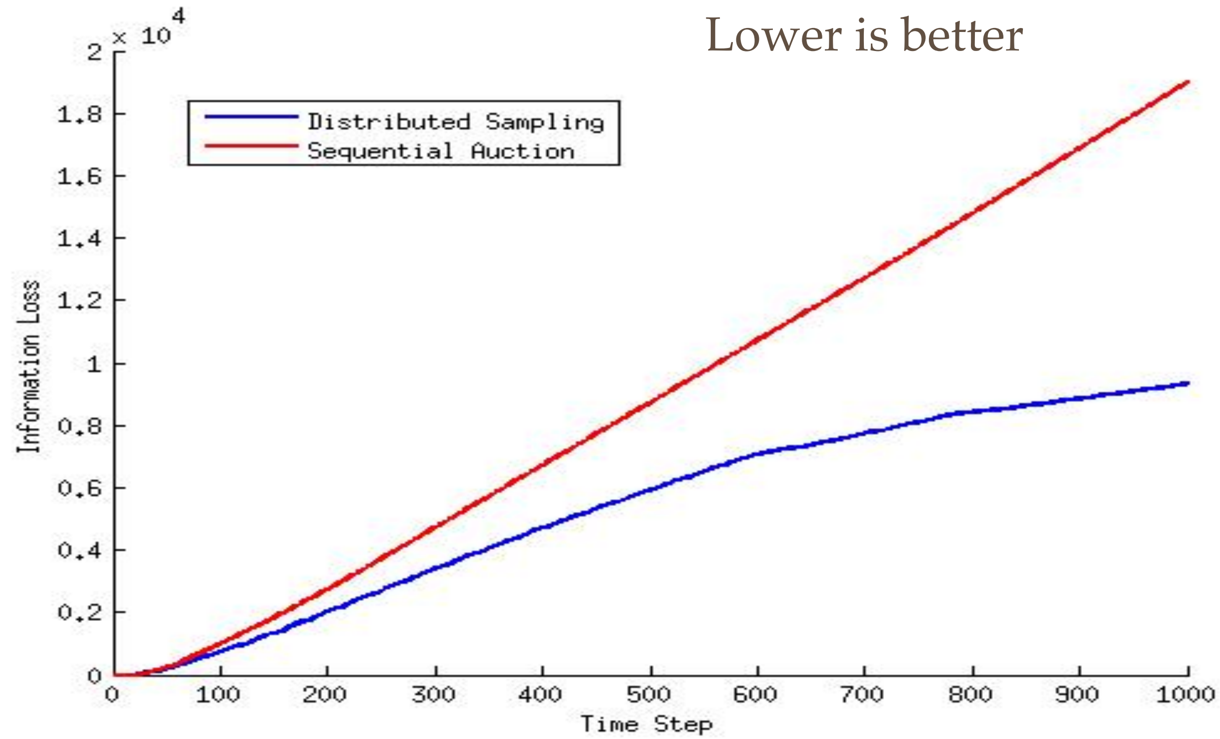
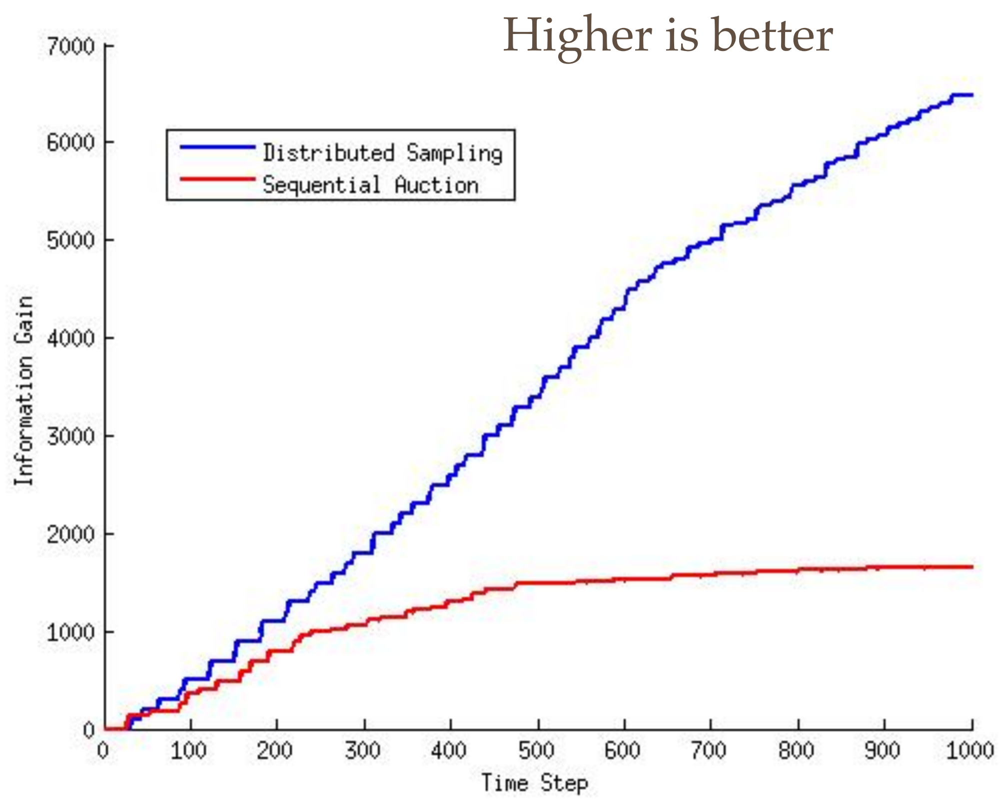
Information Loss (1000 steps)



Information Gain (1000 steps)



Extension

Known environment vs. Unknown environment

- Certain vs. Uncertain

Global communication vs. Limited Communication

- Centralized vs. Decentralized

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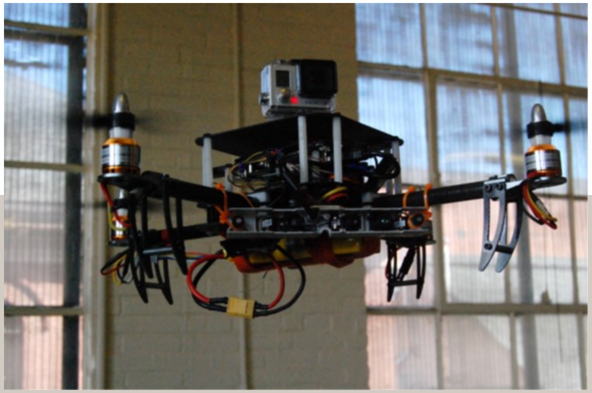
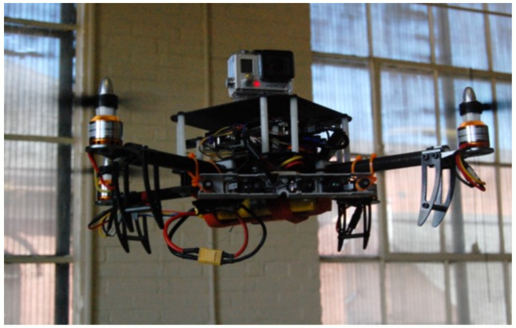
Multi-UAV Explore, Map, And Search in Unknown Environments



Introduction





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Goals

- An approach enable a team of UAVs simultaneously explore, map, and search in unknown environments.
- A mechanism controls the UAVs more focus on one or two sub-tasks (exploration, mapping and search) .
- A communication scheme efficiently the human operators during the mission.

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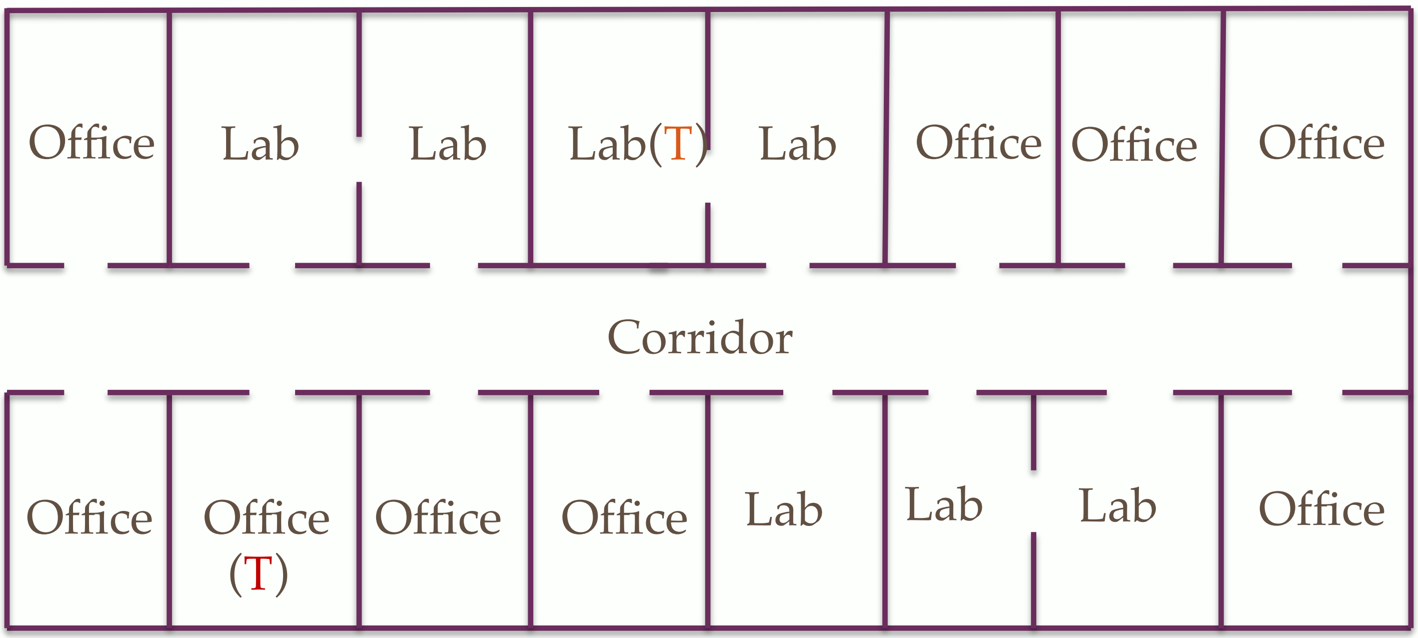
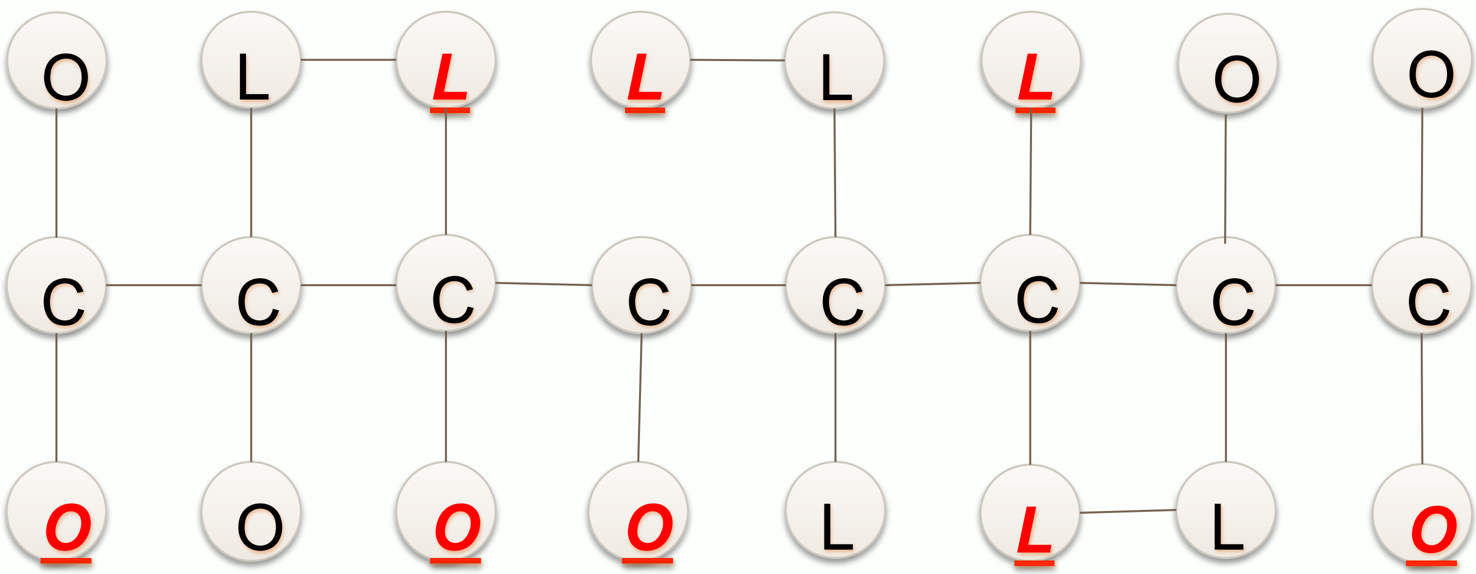
Problem Setup

- Environment
  - Indoor Environment with different types of rooms
  - Some rooms contain targets



Problem Setup

- Topological Representation
  - Model the environment as a graph with rooms as nodes



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UAV Model

- Limited Battery Life

- Equipped with two types of sensors:
  - Observe the room type
  - Observe the target existence
  - Both of the sensors have noise

- Limited communication (disk model)

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UAV Belief State

- Room type (assume UAVs know the all types of rooms)

  For room r, probability of room type:

$$P_r = [P_{t1}, P_{t2}, \ldots P_{tn}] \ (n = |R|)$$

$$\sum_i P_{ti} = 1$$

- Target existence

  For room r, probability of target existence

$$P_t = [P_T, P_F]$$

$$P_T + P_F = 1$$

Priors

- Priors provide the probability of a specific type room contains a target.

Office	Lab	Corridor
0.6	0.7	0.1

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Bayesian Update

- Bayesian Update
  - $P R^{t+1} T = P(T|R)/P(T)\ P(R^{t})$
  - $P T^{t+1} R = P(R|T)/P(R)\ P(T^{t})$
- The posteriors become the new priors.

Reward Function

Robots choose one of the three actions:

- Visit a neighbor node(exploring)

  $I_E = \boldsymbol{I} \alpha^{visited}$ ($\boldsymbol{I}$ is the utility of first visit, $0 < \alpha < 1$)

- Observe for room type (mapping)

  $I_m = -\sum_{r \in R} P_r \log P_r$

- Observe for target (search)

  $I_s = T$, $T \in [0,1]$ *(real utility gain)*

  $I_s = P_T$, $P_T \in [0,1]$ *(estimation)*

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Weighted Sub-goals

Weights are set up to more focus on one or two sub-tasks

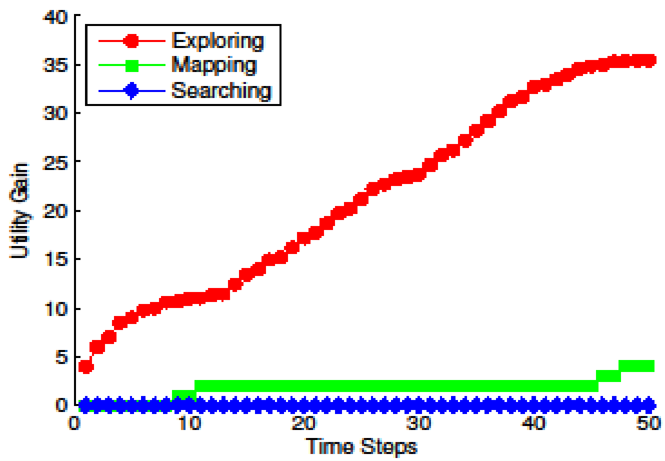
$$\boldsymbol{\omega} = [\omega_e, \omega_m, \omega_s]$$

$$\omega_e + \omega_m + \omega_s = 1$$

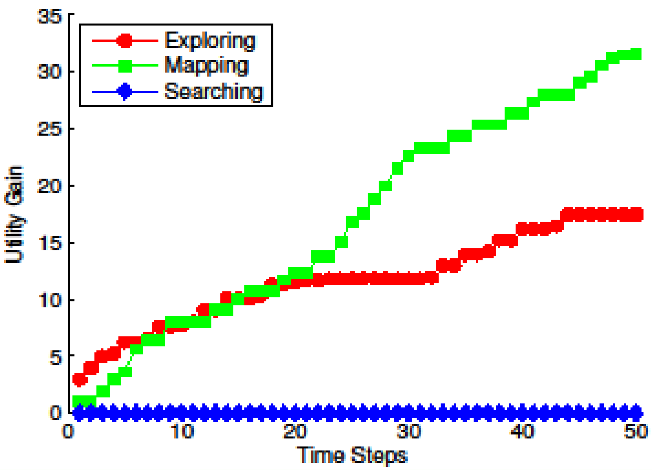
How to apply:

use ω times the estimated reward to generate new estimated reward

Results

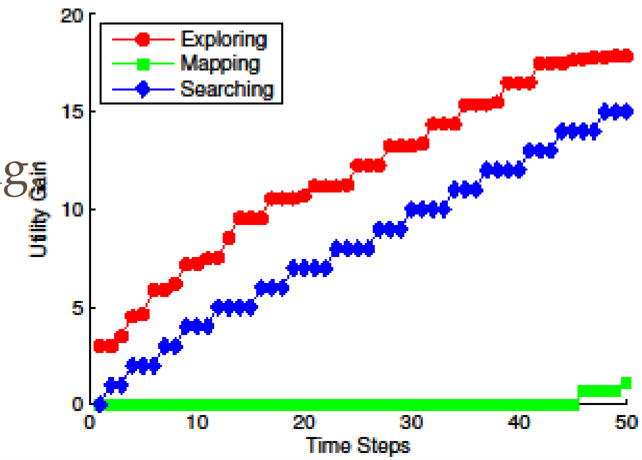


Exploring: 0.9 Mapping: 0.05 Search: 0.05



Exploring: 0.05 Mapping: 0.9 Search: 0.05

Exploring: 0.05 Mapping: 0.05 Search: 0.9



Communication Loss Constraint

A communication loss constraint $\mathcal{S}$ is set up that only allows each UAV lose a valid communication link with human operators no more than $\mathcal{S}$ steps.

Idea: Engage the human operators during the mission

Algorithm: Baseline

- Each UAV selects the action with the best estimated reward.
- Change if conflict with other UAVs with higher estimated reward for the same action.
- Have to select the goals without violate the constraint. Communicate with **base station** (human operators) at least every S steps.

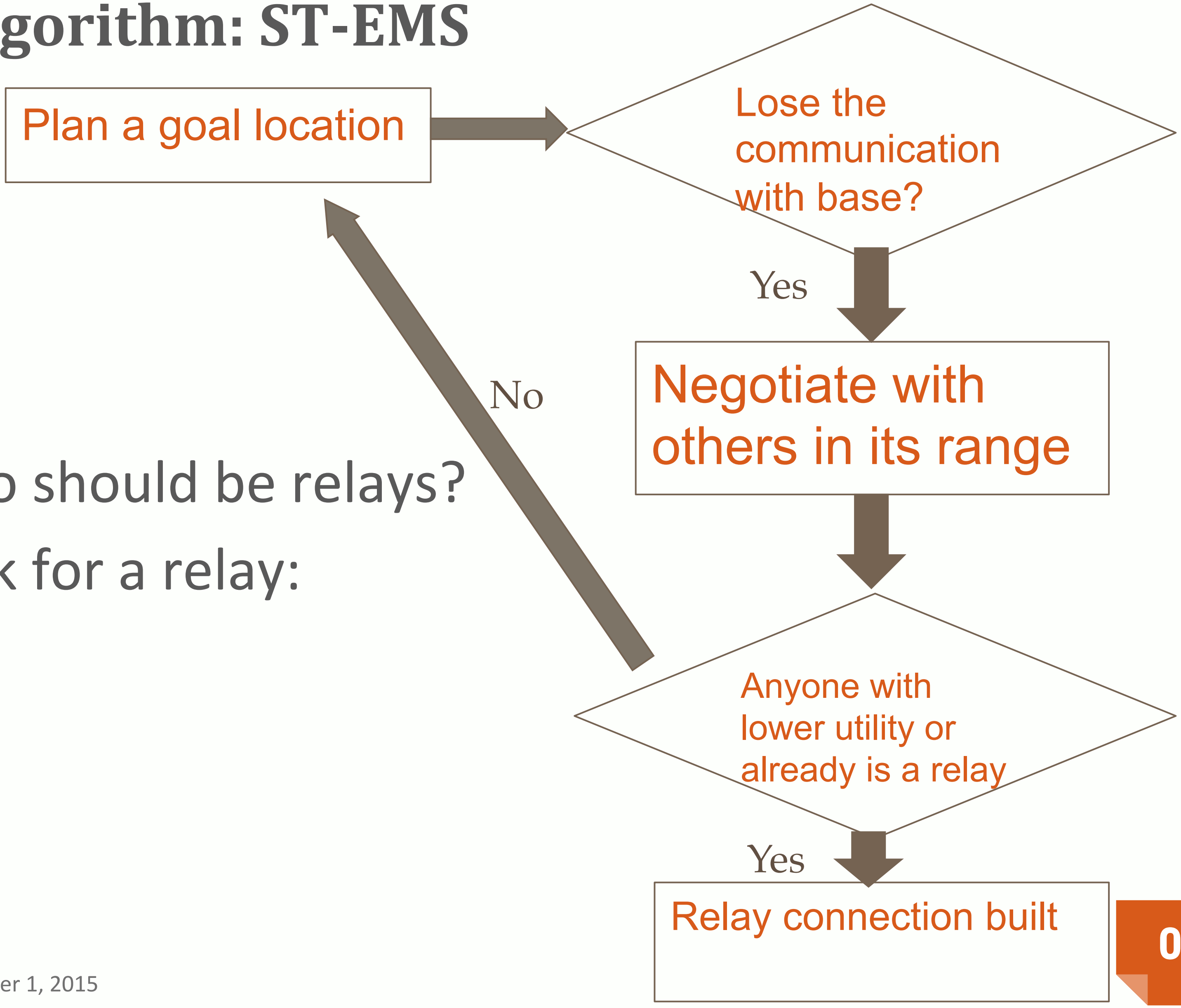
Algorithm: ST-EMS (Steiner Tree – Explore, Map, Search)

Explorer and Relay

- Explorer : explore, map, and search the environment base on the reward functions and weights.

- Relay: retrieve the explorer's information to base station so explorers have more freedom to fulfill the missions.

Algorithm: ST-EMS



Who should be relays?

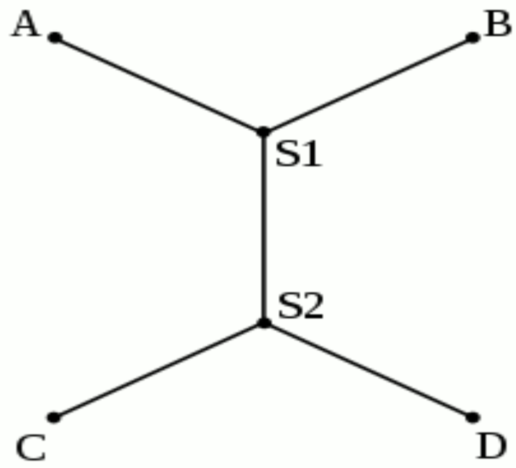
Look for a relay:

Algorithm: ST-EMS

- Find relay locations: Steiner Minimum Tree with Minimum Steiner Points and bounded edge length(*SMT-MSP*)

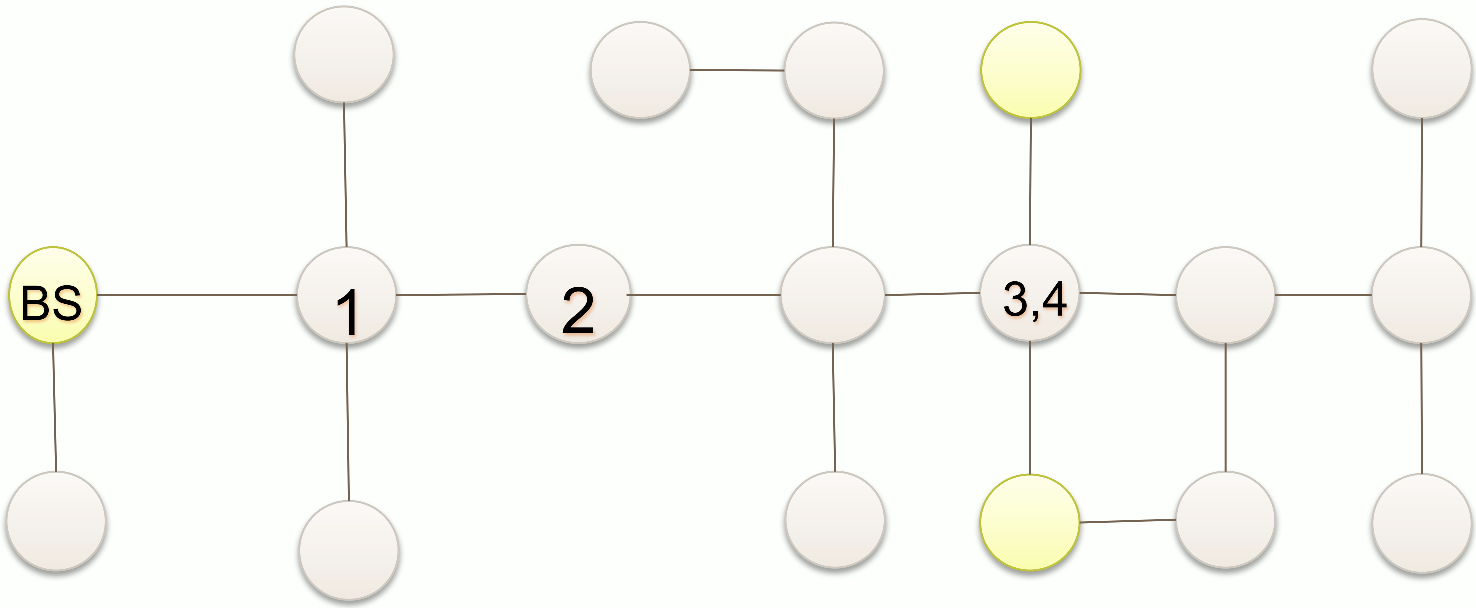
- Steiner Minimum Tree

Given a set *V* of vertices, interconnect them by a graph of shortest length



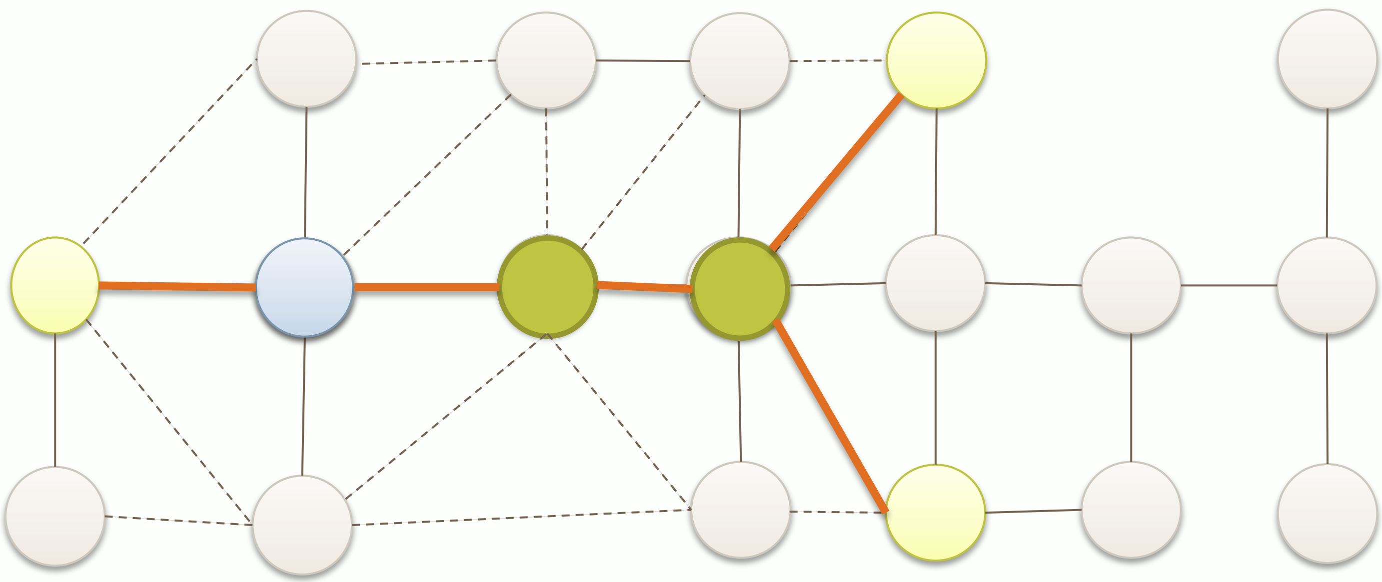
Algorithm: ST-EMS

- *SMT-MSP*
  - *Find the best relay locations*

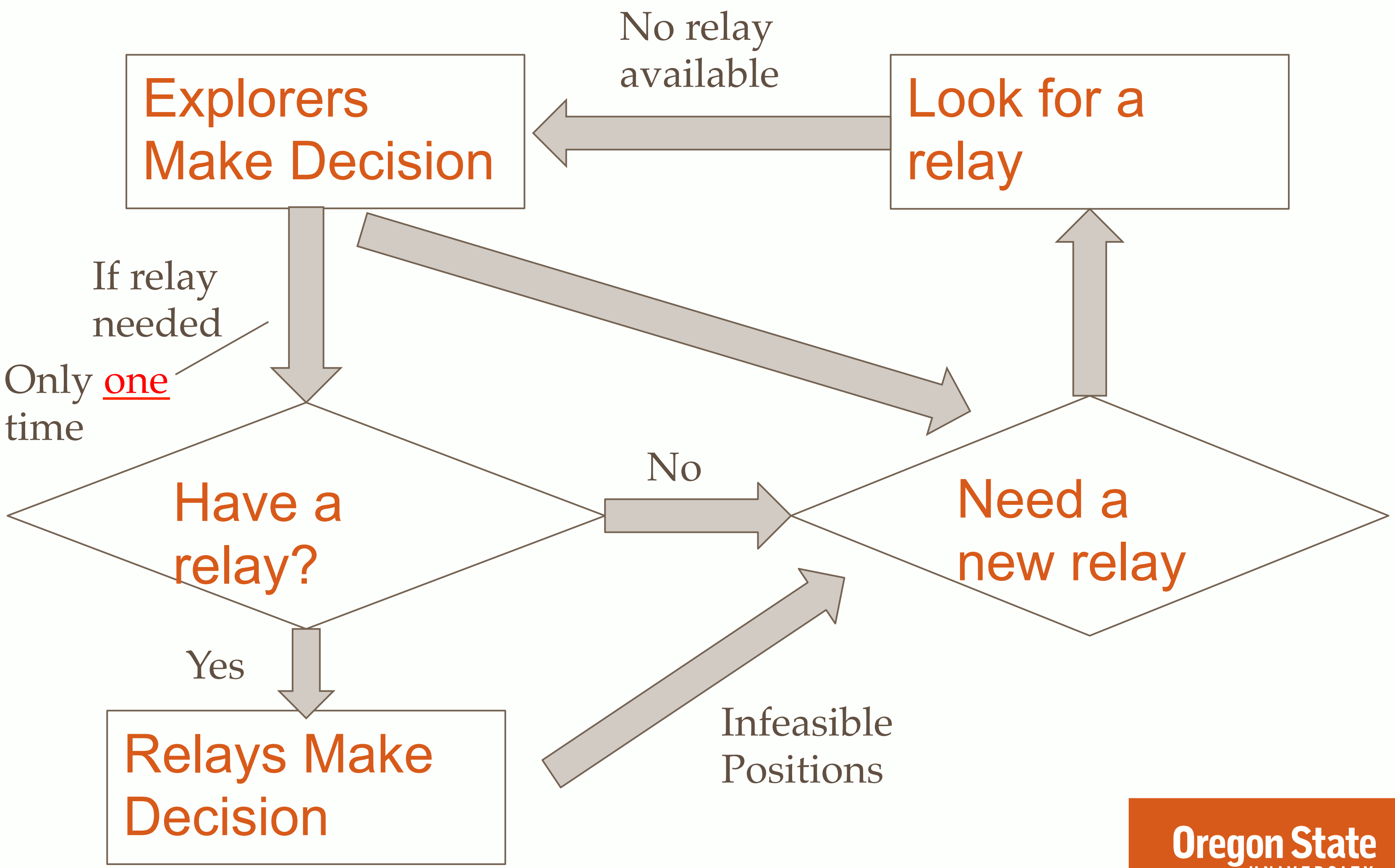


Algorithm: ST-EMS

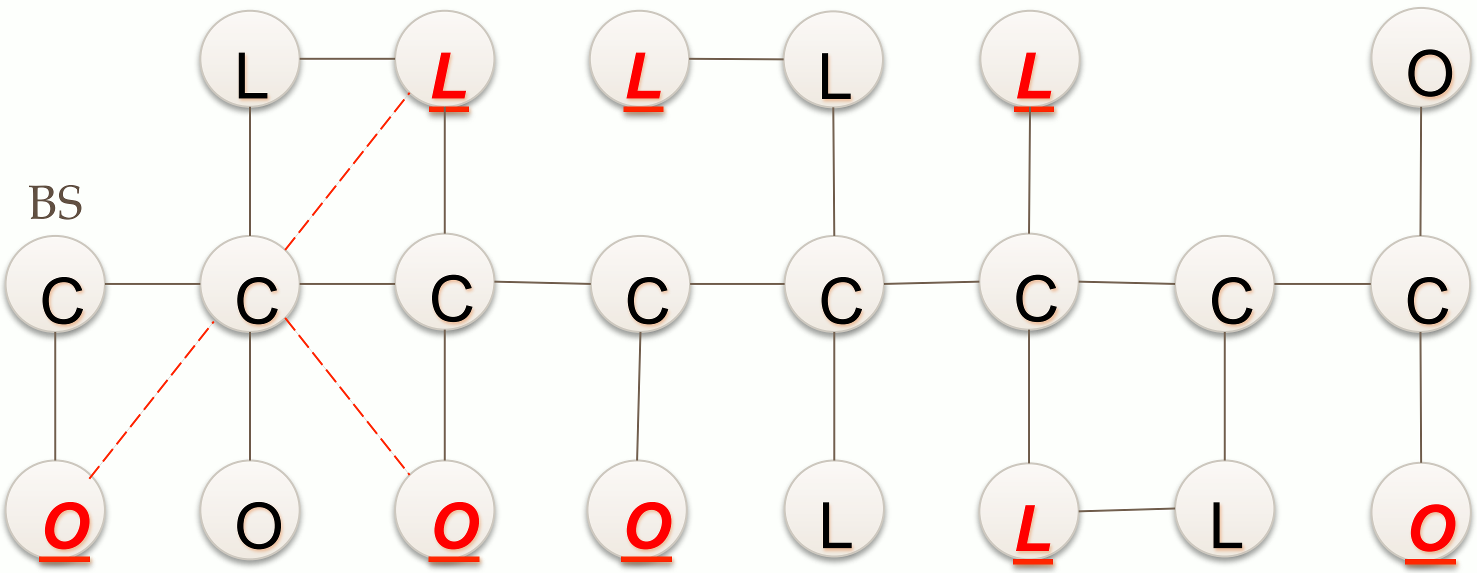
- SMT-MSP is NP-hard (Chen et. al, 2000)
- Greedy approximate(Du and Hu, 2008)



Algorithm: ST-EMS

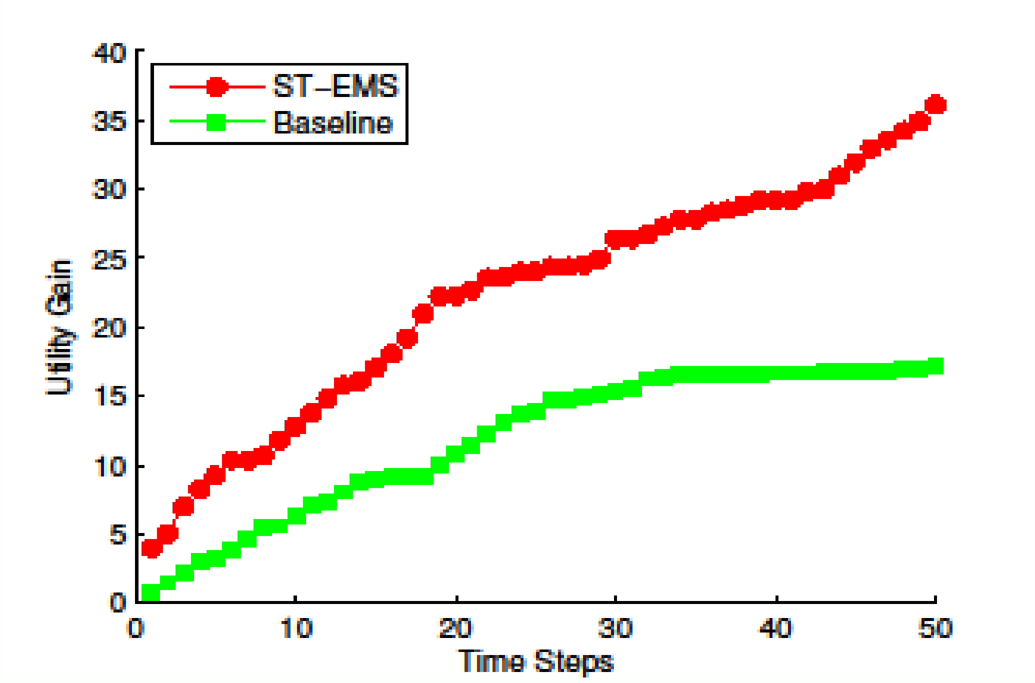


Simulation : Environment



Results

- Total reward gain for both algorithms for 50 steps



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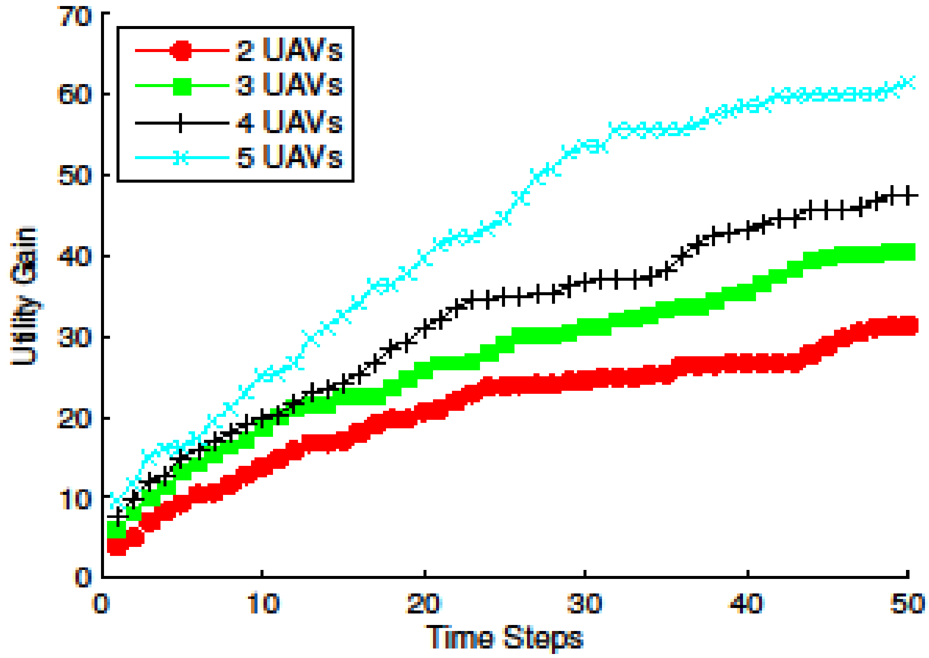
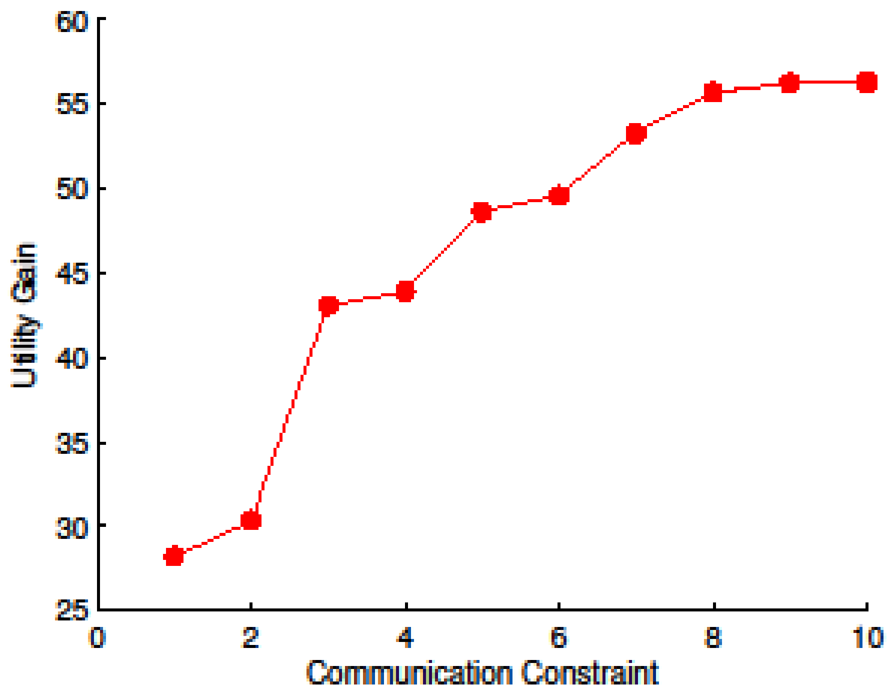
Results

- Scalability: total reward gain for 50 steps

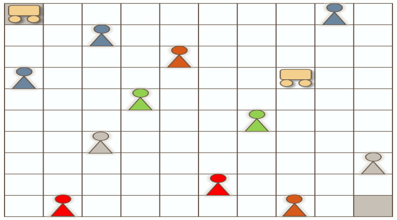
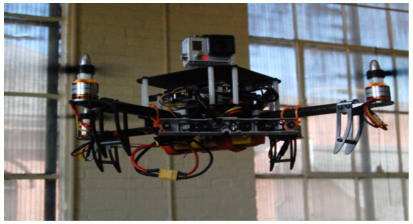


Results

- Reward along with different communication loss constraint



Summary of Contributions

- Known Environment with Global Communication:
  -  An intelligent in orchard auction-based bin-management system
  -  Dynamic information gathering with even workload distribution and RH-based routing
- Unknown Environment with Limited Communication:
  -  Multi-UAV Explore, Map, and Search simultaneously with operator preferences and communication loss constraint

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Conclusion

Multi-robot coordination is difficult because:

- Large state space
- Many action choices
- Dynamic environments

We approach them by:

- Estimating a finite horizon of future changes
- Each robot makes independent decisions while contributing to a common objective
- Underlying representation allows coordination

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Future Work

- Improved future predictions
  - Environment, task, teammates
- Better task decomposition and allocation
  - More sophisticated partitioning, Steiner tree approximation
- Integration with human operators
  - Learning operator preferences across environments
- Implementation: orchard bin management, UAV exploration/ mapping/search

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Acknowledgement

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Questions?