OPTIMIZING THE TRANSPORTATION SYSTEM'S RESPONSE CAPABILITIES

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OUTLINE

- Two response functions:
  1. Transport resources where they are needed
  2. Evacuate people from affected areas

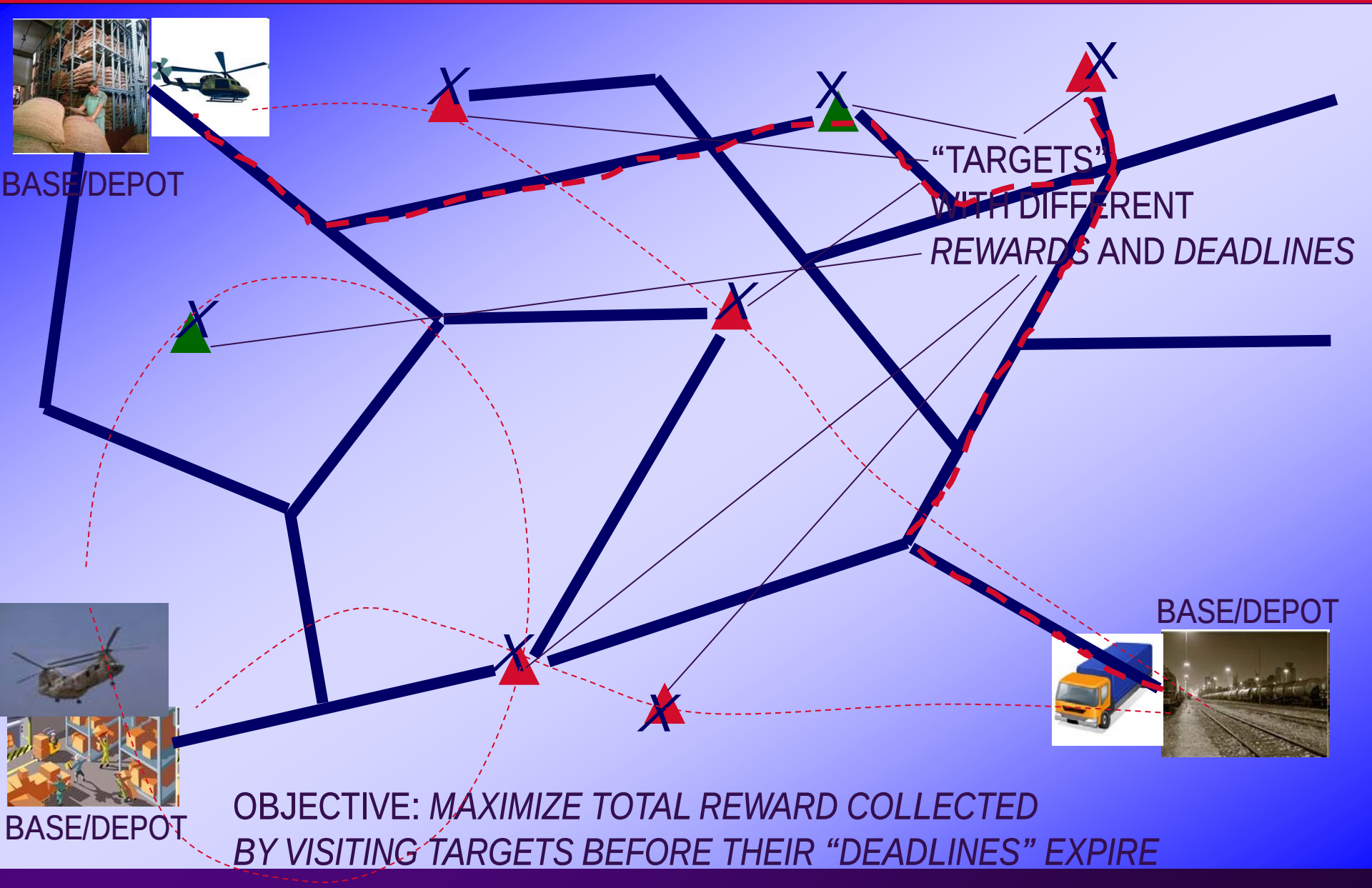
- Methodology for "Resource Transport" function:

  Cooperative Receding Horizon (CRH) optimization:
  - Hedge against uncertainty, react to random events
  - Cooperation among vehicles

- Methodology for "Controlled Evacuation" function:

  Static and Dynamic optimization:
  - Guarantees on worst case delay
  - Cooperation among evacuation vehicles

RESOURCE TRANSPORT MISSION



OBJECTIVE: *MAXIMIZE TOTAL REWARD COLLECTED BY VISITING TARGETS BEFORE THEIR "DEADLINES" EXPIRE*

RESOURCE TRANSPORT MISSION

CONTINUED

This is like the notorious TRAVELING SALESMAN problem, except that…

- … there are multiple (cooperating) salesmen
- … there are deadlines + time-varying rewards
- … environment is stochastic
  (vehicles may fail, new targets emerge, etc.)

SOLUTION APPROACHES

- Stochastic Dynamic Programming – *Wohletz et al, 2001*

  Extremely complex…

- Functional Decomposition:
  - Dynamic Resource Allocation – *Castanon and Wohletz, 2002*
  - Assignment Problems through Mixed Integer Linear Programming – *Bellingham et al, 2002*

    Combinatorially complex…
  - Path Planning – *Hu and Sastry, 2001, Lian and Murray 2002, Gazi and Passino, 2002, Bachmayer and Leonard, 2002*

COMBINATORIAL + STOCHASTIC COMPLEXITY

1. Target Assignment → 2. Routing → 3. Path Control

MANAGING UNCERTAINTY: CONTRAST TWO APPROACHES

ESTIMATE-AND-PLAN

- Decisions planned ahead
- Need accurate stochastic models
- Curse of dimensionality

- Dynamic Programming (DP)
- Markov Decision Processes (MDP)

VS

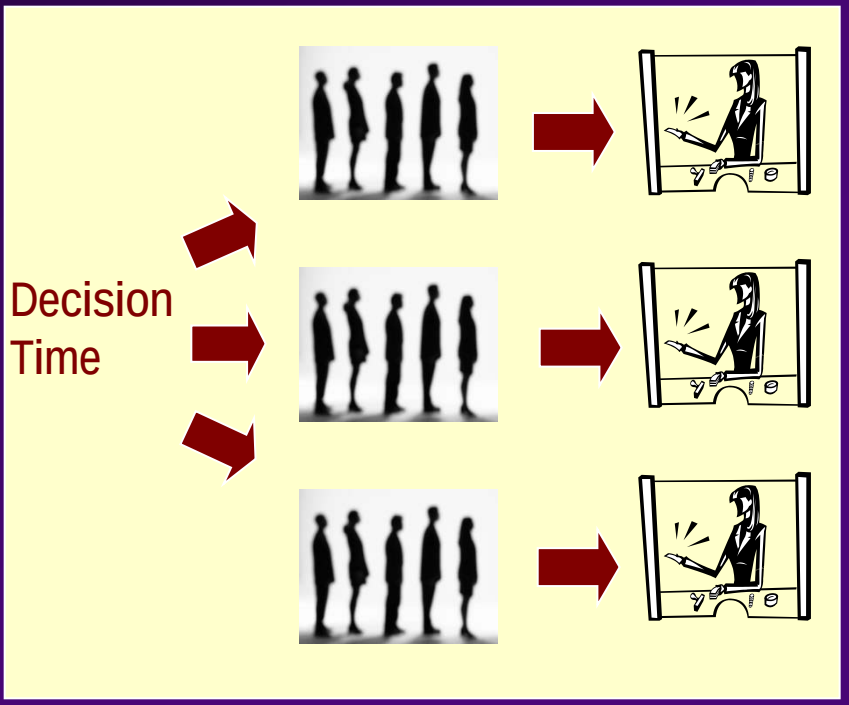
HEDGE-AND-REACT

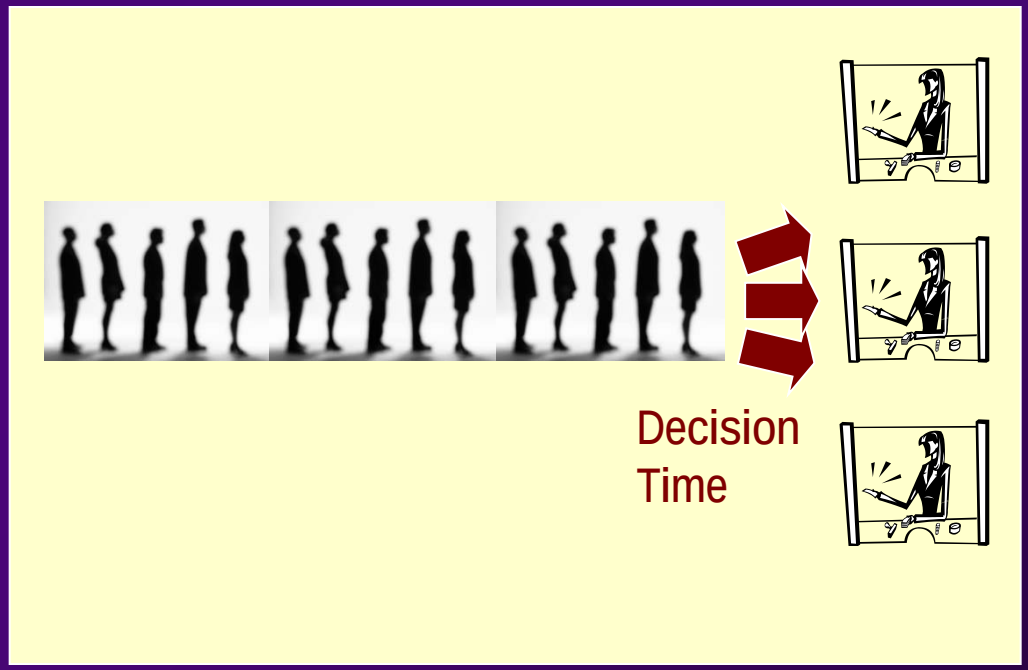
- Delay decisions until last possible instant
- No (detailed) stochastic model
- Simpler opt. problems

- Receding Horizon Control (RHC)
- Model Predictive Control (MPC)

UNCERTAINTY: CONTRAST TWO APPROACHES

ESTIMATE-AND-PLAN VS HEDGE-AND-REACT





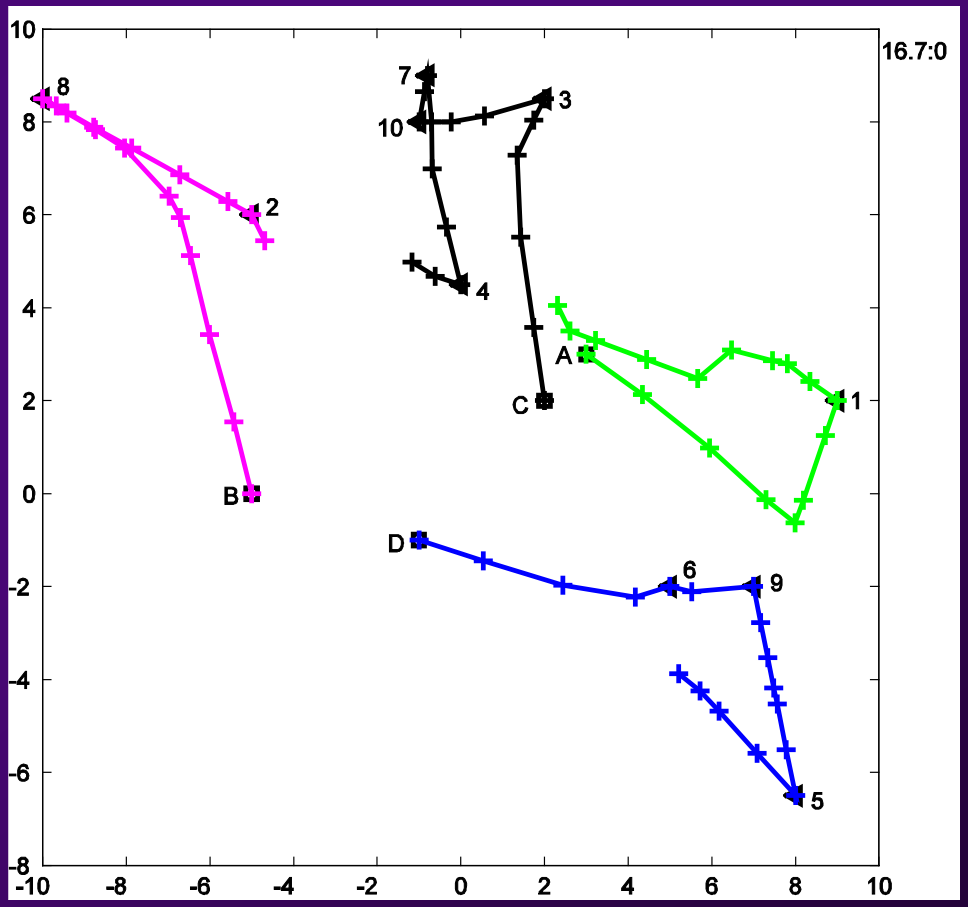
COOPERATIVE RECEDING HORIZON (CRH) CONTROL: *MAIN IDEA*

MAIN IDEA IN CRH APPROACH:

Replace complex *Discrete Stochastic Optimization* problem by a sequence of simpler *Continuous Optimization* problems

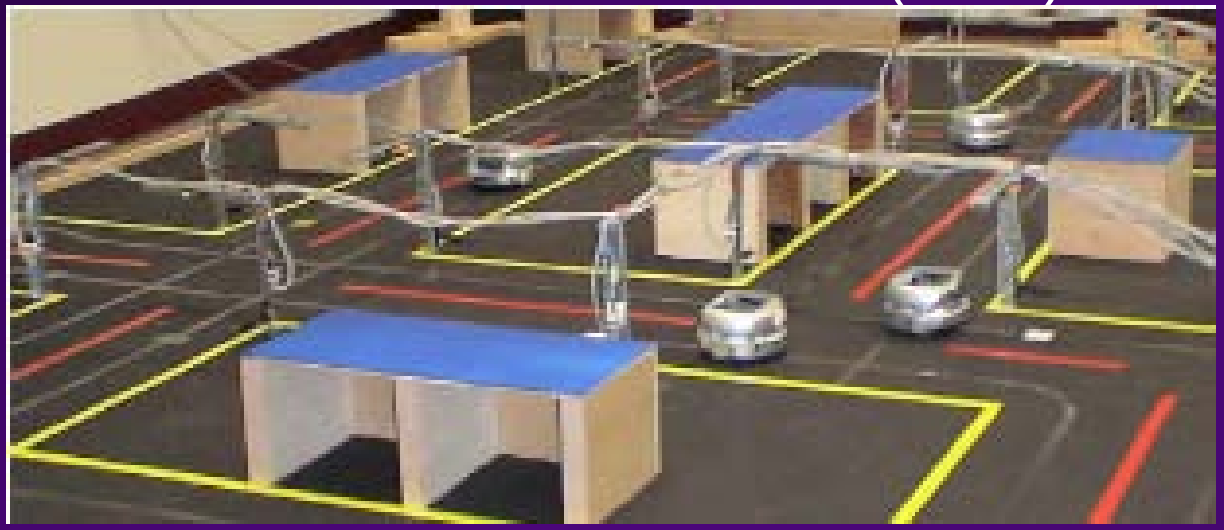
Can guarantee that vehicles ultimately head for the desired DISCRETE TARGET POINTS

Li and Cassandras, *IEEE Trans. on AC*, 2006



BOSTON UNIVERSITY TEST BEDS

RoboticUrban-like Environment (RULE)



CRH Test Bed with autonomous robots

New autonomous robots

CONTROLLED EVACUATION

- Consider post-disaster evacuation of an area.

  A **Network** with **nodes** where people gather/shelters and **links** corresponding to modes of transportation (e.g.,roads, rail, air)

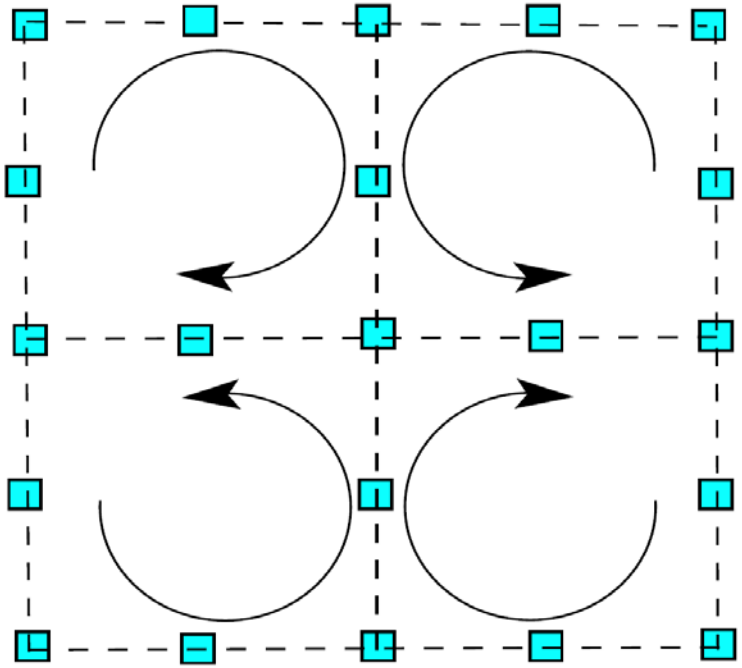
- Two scenarios:
  - **Static View:** affected area is stable and evacuation is orderly; design routes for vehicles to minimize delay
  - **Dynamic View:** affected area is dangerous; respond dynamically to evacuation requests

THE STATIC VIEW

- Utilize multiple vehicles
- Assign each one a subset of nodes
- People can be transferred among vehicles to increase efficiency

Ferry Relaying Algorithm (FRA)

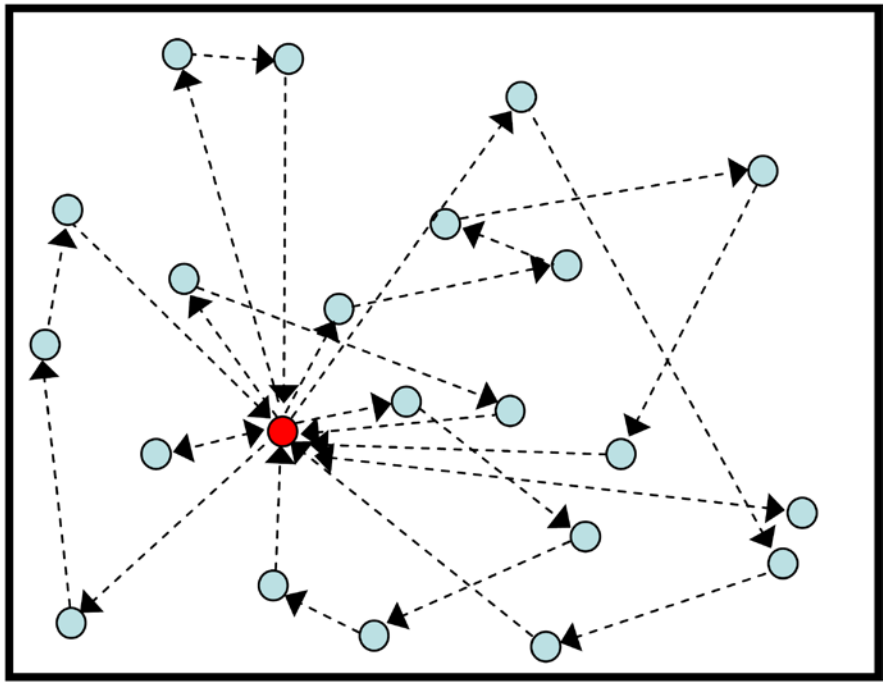
(Zhao et al., 2005)



contiguous

Centralized Vehicle Relaying (CVR)

(Paschalidis and Moazzez-Estanjini, 2010)



non-contiguous

CVR FEATURES

- **Performance guarantees:** bounds on average time and maximum time required to transport an individual from a node to the shelter

- **Scalable**: if number of vehicles *M* scales linearly with the number of nodes *N*, then constant (in *M* and *N*) per node throughput with constant worst-case delay is achievable

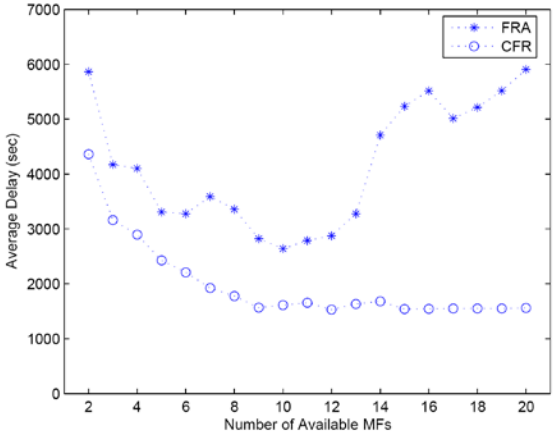
SIMULATION RESULTS

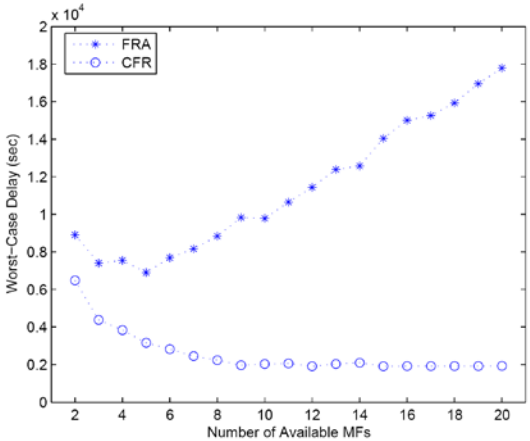
Simulation setting:

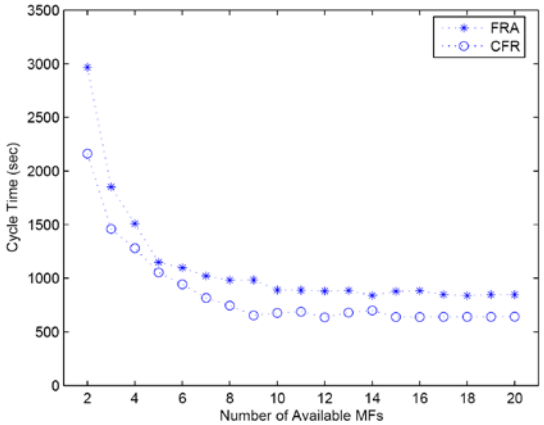
Node placement pattern:
(i) *Uniform*
(ii) *Cluster-based*

Individual gathering model:
(i) *Uniform*
(ii) *Non-uniform*

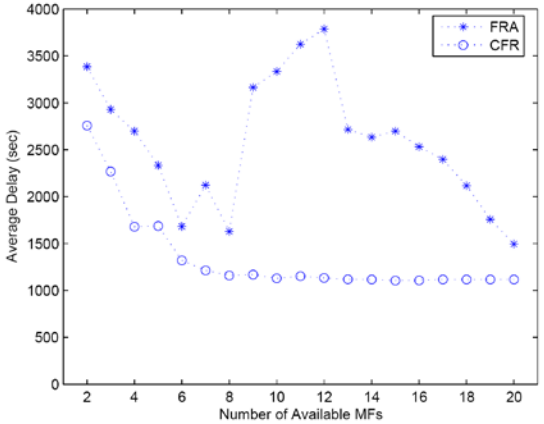
Uniform model:

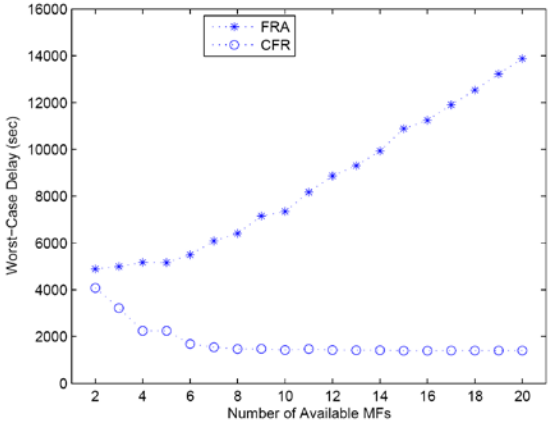


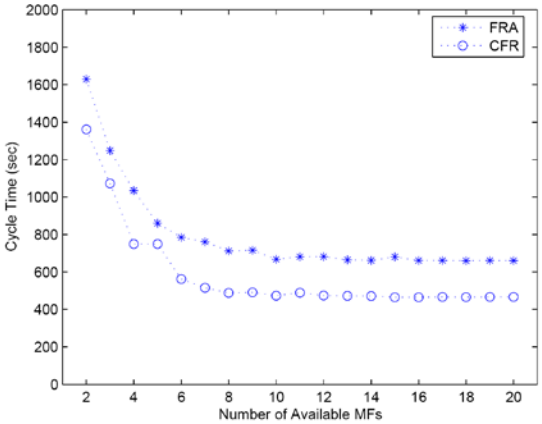




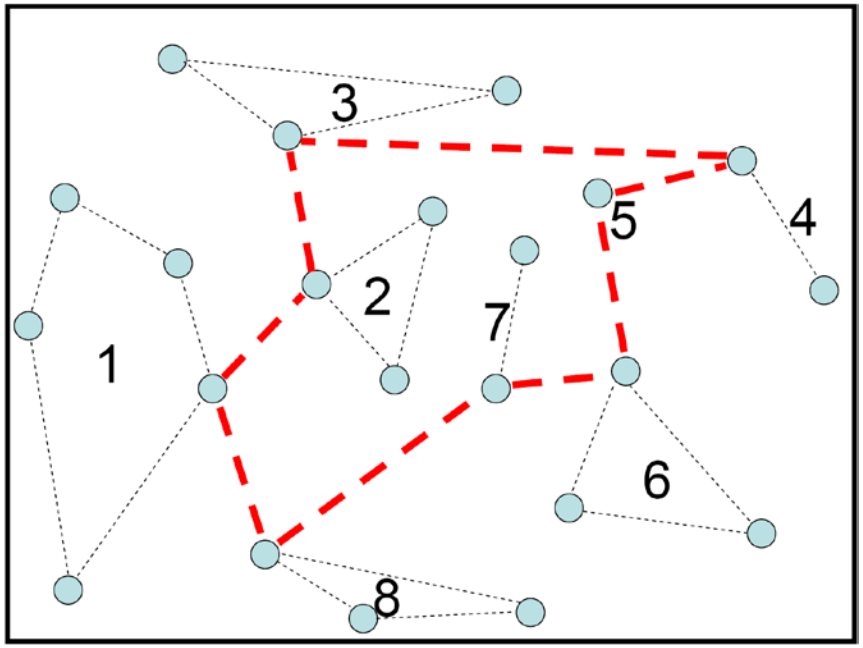
Non-uniform model:







ALTERNATIVE SCHEME: BUS VEHICLE RELAYING (BVR)



- Utilize multiple vehicles and assign to each vehicle a **"neighborhood"** containing some evacuation points

- A **"bus"** meets with the vehicles and transfers people to shelters outside the neighborhood

THE DYNAMIC VIEW

- Affected area is not stable and safe.
- Rate of gathering of people is highly variable.

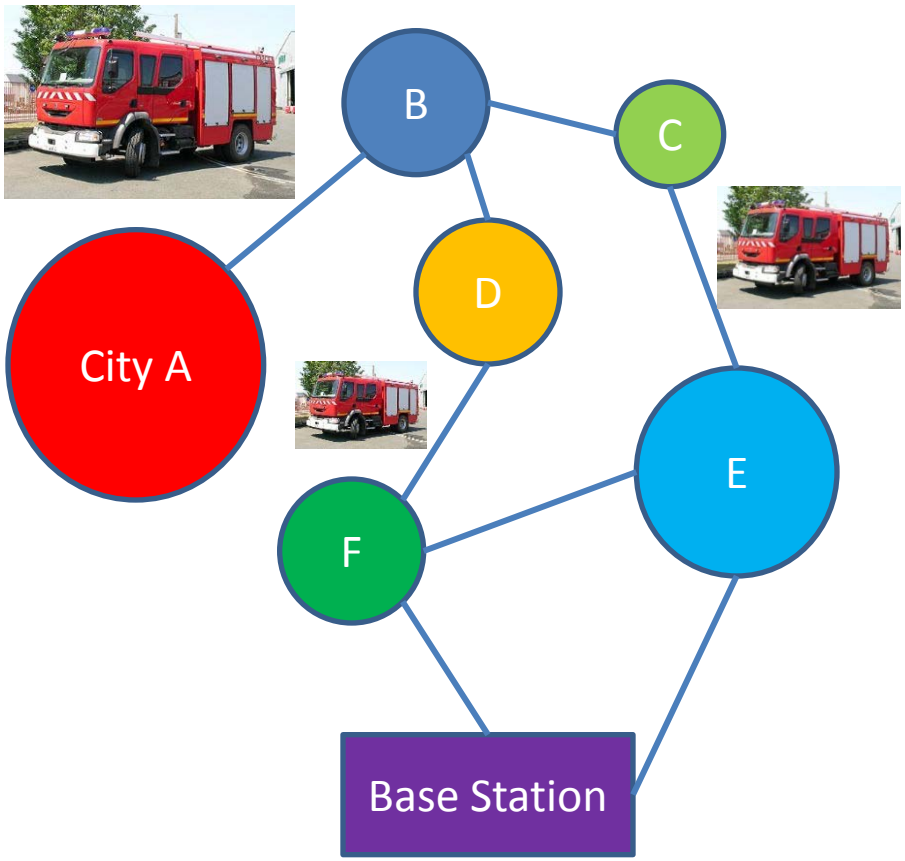
$\Rightarrow$ Periodic schemes not appropriate.

- Vehicles respond to evacuation requests as they emerge.
- Wireless communication between nodes and vehicles.

PROBLEM FORMULATION

- 2-dimensional coverage area, *S*, *N* nodes.
- R_k^i: reward at node *i*.
- *M* vehicles, C_k^j: capacity of vehicle *j*.
- Vehicles navigate in *S*, collect rewards.
- Vehicles return to a depot to replenish.
- Vehicles sense "intensity signals" from nodes.
- Goal: Find policy to maximize reward collection.
- A dynamic programming problem

Similar to
RESOURCE TRANSPORT MISSION



- Circle size proportional to reward
- Vehicle size proportional to capacity

APPROXIMATE DYNAMIC PROGRAMMING

- Standard DP algorithms suffer from curse of dimensionality.

- Approximate Dynamic Programming (ADP)
  - Actor-Critic algorithms
    [Konda and Tsitsiklis, 2003]
    - Policies parameterized by lower dimensional vector ϑ.
    - Optimizes policy using a simulation of the MDP.
  - Distributed Multi-agent Actor-Critic
    [Pennesi and Paschalidis, 2010]
    - Multiple agents simultaneously explore the space.
    - Policy update follows a consensus-like algorithm.

DIRECTIONS TO EXPLORE

- 3-dimensional coverage areas.
  - Airborne vehicles evacuating mountainous areas.

- Transportation infrastructure:
  - Mission space is a transportation graph.
  - Vehicles are moving on the graph.
  - Use hop-count to measure distances.

- Additional constraints:
  - Vehicle “rendez-vous” at targets
  - Fuel constraints

- Optimal Base/Depot location

- Human Factors
  - Controller Credibility, Guarantees
  - Fairness