Efficient Ad-Hoc Routing and Field Coverage Through **Detour-Based Mobility Coordination**

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Joint work with

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The setting

- Sensors (video, pollution, …)
  - Cannot be deployed at a high-enough density
  - Available with, or mounted on mobile agents
- Agents (taxis, robots, 1st responders, …)
  - Have independent primary tasks or missions
  - Subject to scheduling constraints
- Field (city, disaster area, natural park, …)
  - Space where agents roam to fulfill their missions
  - Space over which sensor queries are submitted

Mobility as a controllable resource

- Mobility = Freedom to move
  - Agent schedules may have slack giving them "freedom" to take detours in their journeys
- Aggregate Mobility = System Resource
  - The aggregate mobility of a set of agents can be viewed as a resource only if it is possible to coordinate (control) it

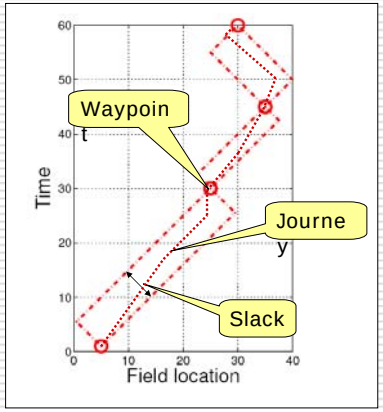
Mobility coordination: Applications

- DTN Routing
  - ➔ Use slack to improve delivery
- Field Monitoring
  - ➔ Use slack to improve query responses

Slack in agent journey in a field

Agent mission dictates a schedule for rendezvous at various field locations

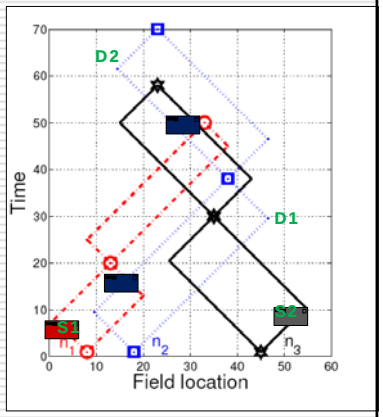
Location	Time
5	1
25	30
35	45
30	60



Coordination = better routing

Plan agent encounters to improve DTN routing

n_1	
time	location
1	8
20	13
50	33
n_2	
time	location
1	18
38	38
70	23
n_3	
time	location
1	45
30	35
58	23



Problem Definition

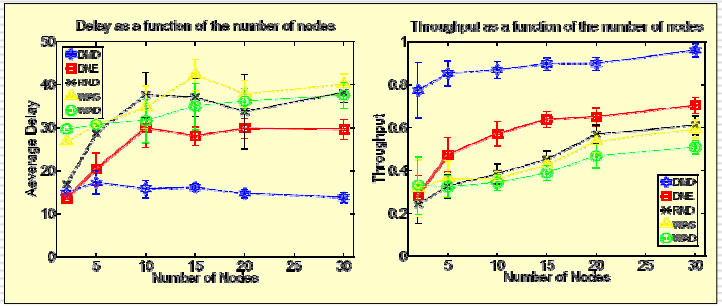
- Given
  - A set of *n* mobile agents
  - Each has a set of waypoint constraints {(*loc*,*t*)}
  - A set of messages to be delivered {(*loc1*,*loc2*,*t*)}
- Find additional waypoints so as to
  - Minimize the average message delivery delay
  - Maximize the number of delivered messages
  - *... etc.*
- NP-hard problem ~ Hamiltonian cycle

Solutions (Heuristics) considered

- Detour for Message Delivery (DMD)
  - Centralized
  - Workload-aware
  - Shortest-path routing
- Detour for Node Encounters (DNE)
  - Distributed
  - Workload-oblivious
  - Uses flooding

+ Baseline approaches (RND, WAS, WAD)

Coordination = better routing

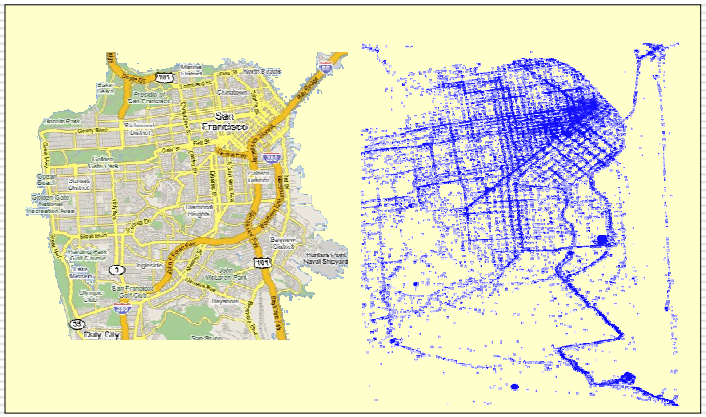


Random Waypoint Mobility with 10% slack
Poisson message arrival process with mean = 2
Source-destination uniformly distributed over a 30 x 30 field
20 simulations, each is 100 seconds, 95% confidence intervals shown

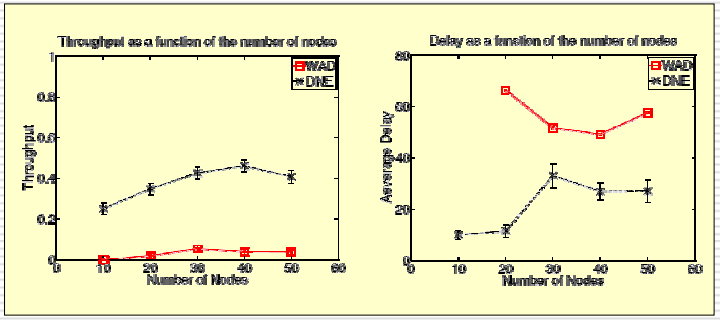
Trace-driven evaluation

- San Francisco Taxi traces
  - Trace length = 25 hours
  - Data = (Id, Location, Time, Status)
- Trace used to
  - Construct map of streets used by taxis
  - Obtain maximum speed (limit) for each street
  - Obtain schedule of taxi journeys (time and location of client drop-off and pick-up)

Trace-driven evaluation



Trace-driven evaluation



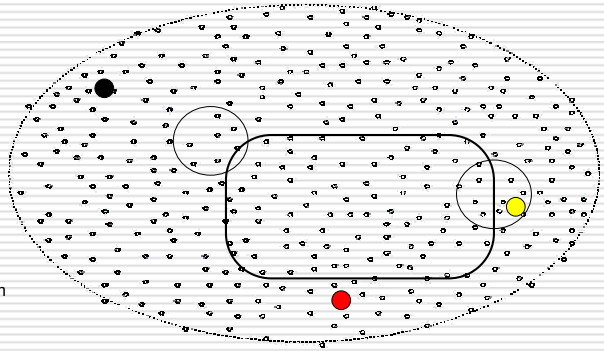
Topology of streets and traffic patterns limit mobility!
But still significant improvement over no coordination!

Related Work†

- Helping nodes (infrastructure)
  - Message ferries
  - Data mules

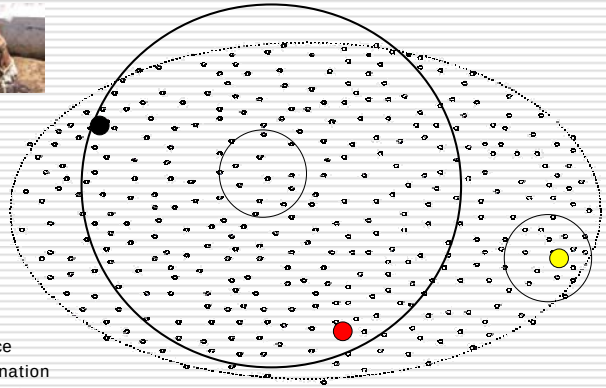
† W. Zhao, M. Ammar, and E. Zegura. A message ferrying approach for data delivery in sparse mobile ad hoc networks. In MobiHoc '04: Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing, pages 187–198, New York, NY, USA, 2004. ACM Press.

Message Ferry



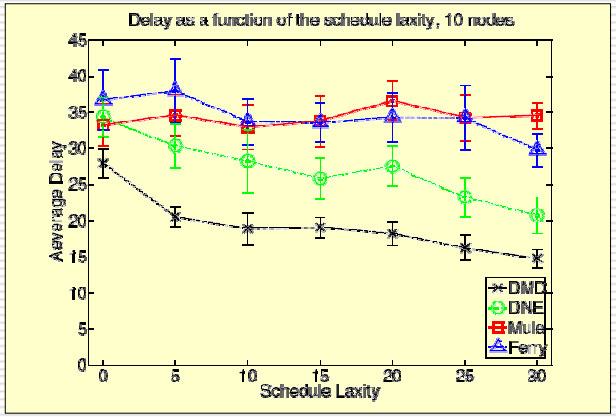
Source
Destination
Ferry
Ferry Route

Data Mules

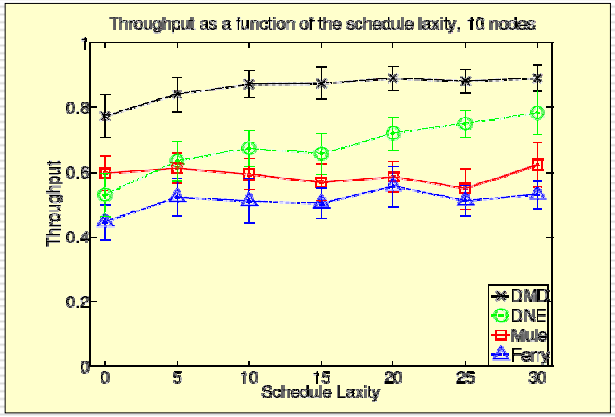


Source
Destination
Mobile Element

Effect of Slack: Delay



Effect of Slack: Throughput



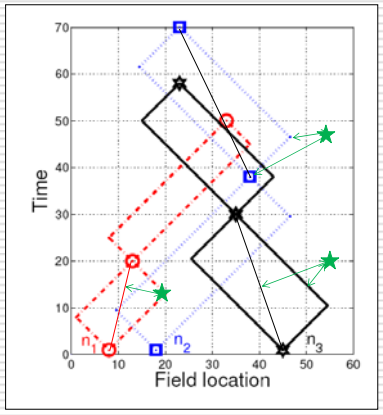
Mobility coordination: Applications

- DTN Routing
  - ➔ Use slack to improve delivery
- Field Monitoring
  - ➔ Use slack to improve query responses

Coordination = better coverage

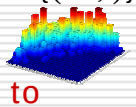
Increase probability of accurate answers to spatial queries

n_1	
time	location
1	8
20	13
50	33
n_2	
time	location
1	18
38	38
70	23
n_3	
time	location
1	45
30	35
58	23



Problem Definition (stochastic flavor)

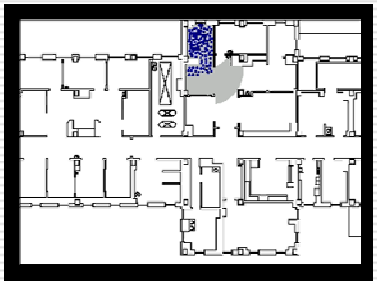
- Given
  - A set of *n* mobile agents
  - Each has a set of waypoint constraints $\{(loc,t)\}$
  - A monitoring preference distribution



- Find additional waypoints so as to
  - Minimize spatio-temporal error of responses
  - Maximize query success rate subject to accuracy constraints
  - … *etc.*
- NP-hard problem!

Related Work†

Movie by Andrew Howard

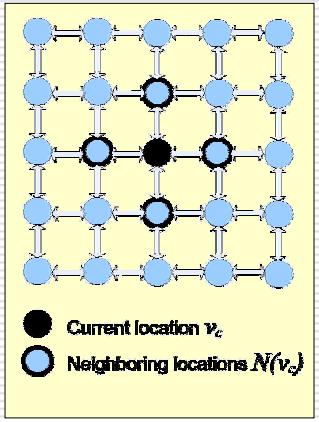


- Agents are not autonomous
- Assumes high-density of sensors
- No mobility in steady-state
- Uncovered areas cannot be queried with any accuracy

† Andrew Howard, Maja J. Mataric, and Gaurav S. Sukhatme. *Mobile sensor network deployment using potential fields: A distributed, scalable solution to the area coverage problem*. In 6th International Symposium on Distributed Autonomous Robotics Systems (DASR02), June 2002.

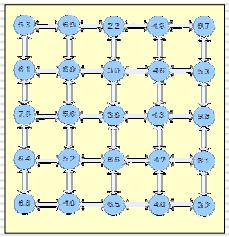
Targeted Field Monitoring (TFM)

- A distributed algorithm, where each node:
  1. Assigns a utility to each neighboring location (on a grid)
  2. Greedily moves to the feasible location with the highest "potential" utility



Utility of a location

- Local view of agent i (C_i):
  - Last time location was visited by *any* agent
  - *Updated on two occasions*
    - *Agent visits location*
    - *Update from another agent*



- Utility of location v to agent i
  - $U_i(v) = D(v)*(time - C_i(v))$

  where $D(v)$ is preference for v

Potential utility of a location

- Potential Future Paths (PFP) are all the feasible paths
- Potential utility of a location is the sum of the utilities of locations on the best PFP within a locale
- Locale defined using a distance (radius) h

Theorem: Radius h need not be larger than the slack!

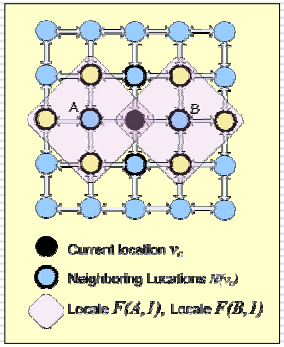
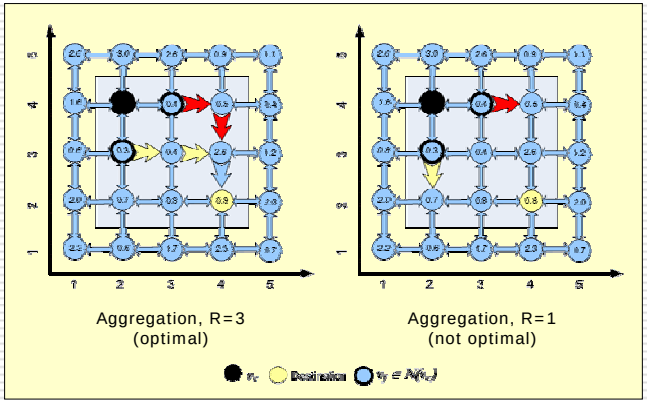
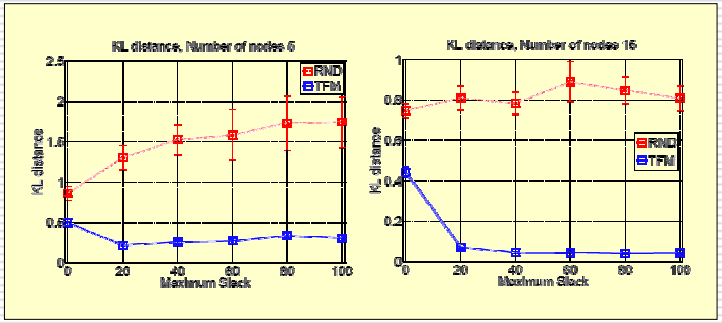


Illustration of TFM

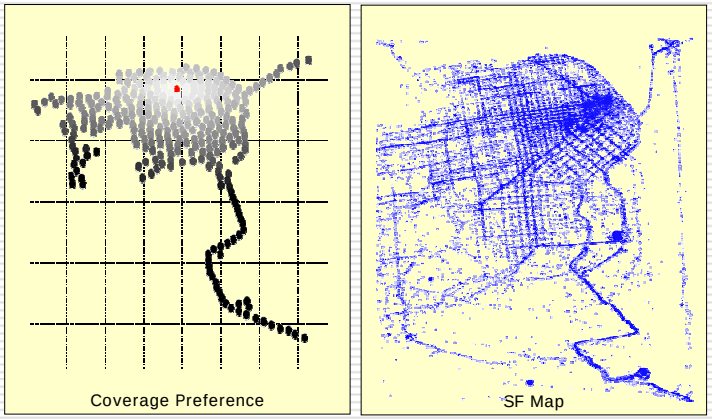


Coordination = better coverage

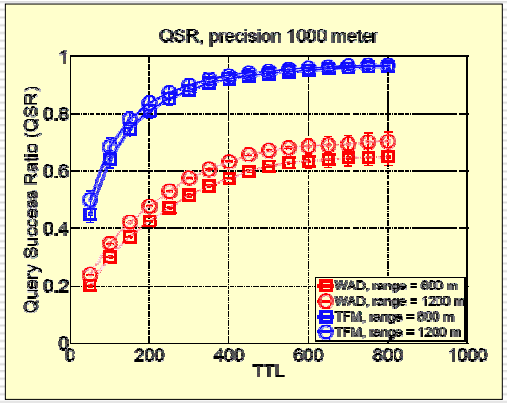


Results for uniform preference with RWP mobility model

Trace-driven evaluation



Trace-driven evaluation



Trace-driven evaluation

- Effect of increased radius (lookahead)

h_{max}	0	1	2	3
KL distance	1.0986	0.8975	0.7441	0.6528

Summary

- Mobility is an important resource to be managed
- Could yield significant improvements for many applications
  - DTN Routing
  - Field Monitoring

Preferential Field Coverage Through Detour-Based Mobility Coordination

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http://www.cs.bu.edu/groups/wing

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