Adaptive Communication Networks for Heterogeneous Teams of Robots

Stephanie Gil

PhD Thesis Defense

Dec 4, 2013

Motivational Example

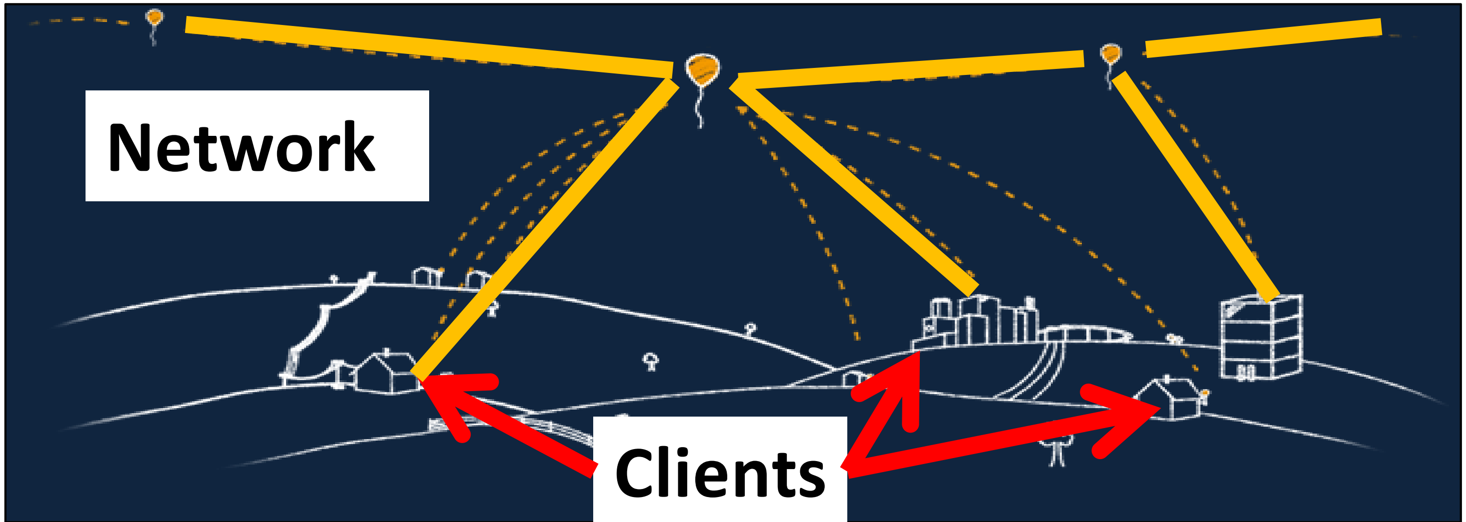
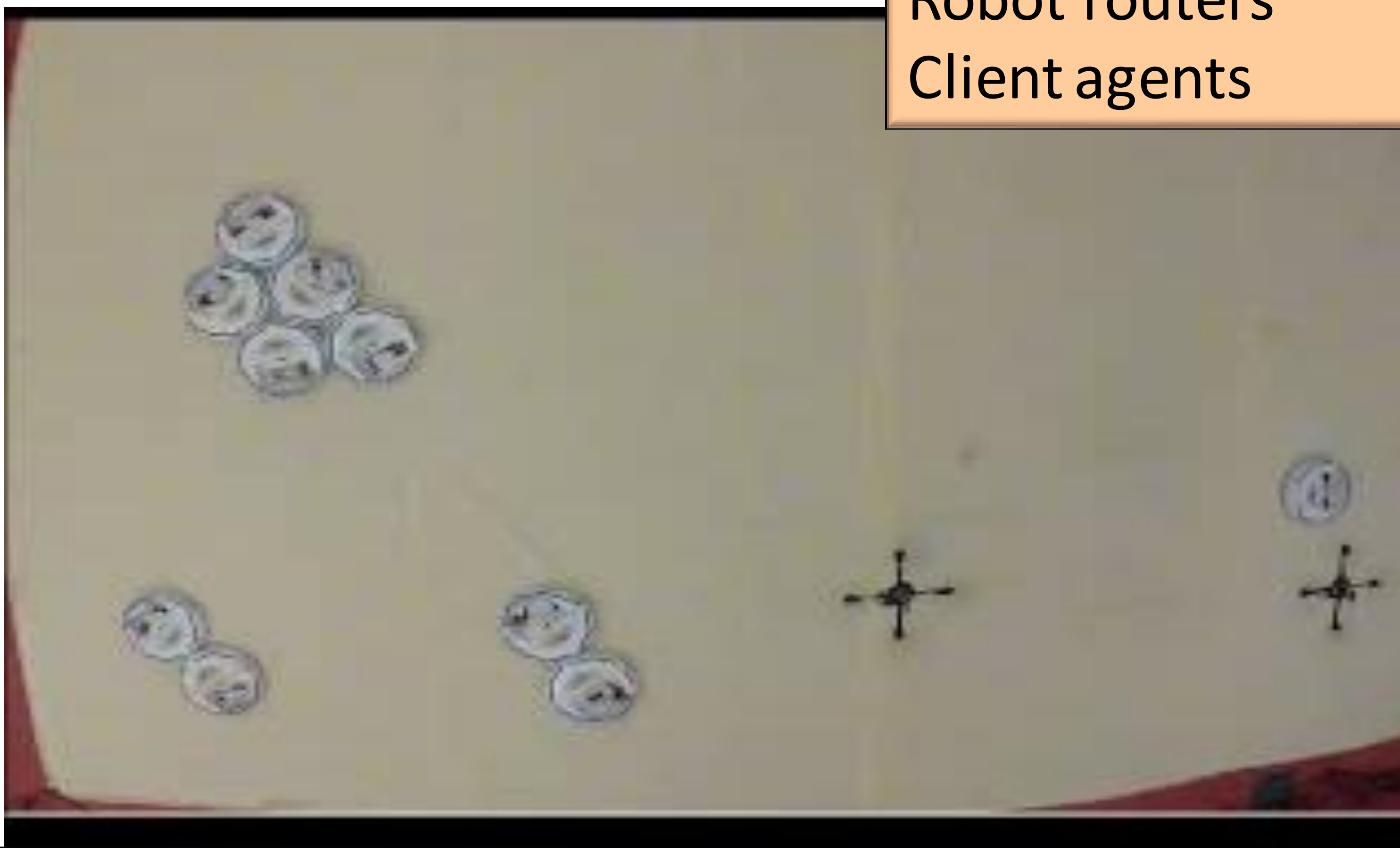


Photo Credit: www.google.com/loon

Question: Use position to satisfy demands?

Our Objective

Heterogeneous system:
Robot routers
Client agents



Client agents move over unknown trajectories → Routers move to provide demanded communication

Future Applications

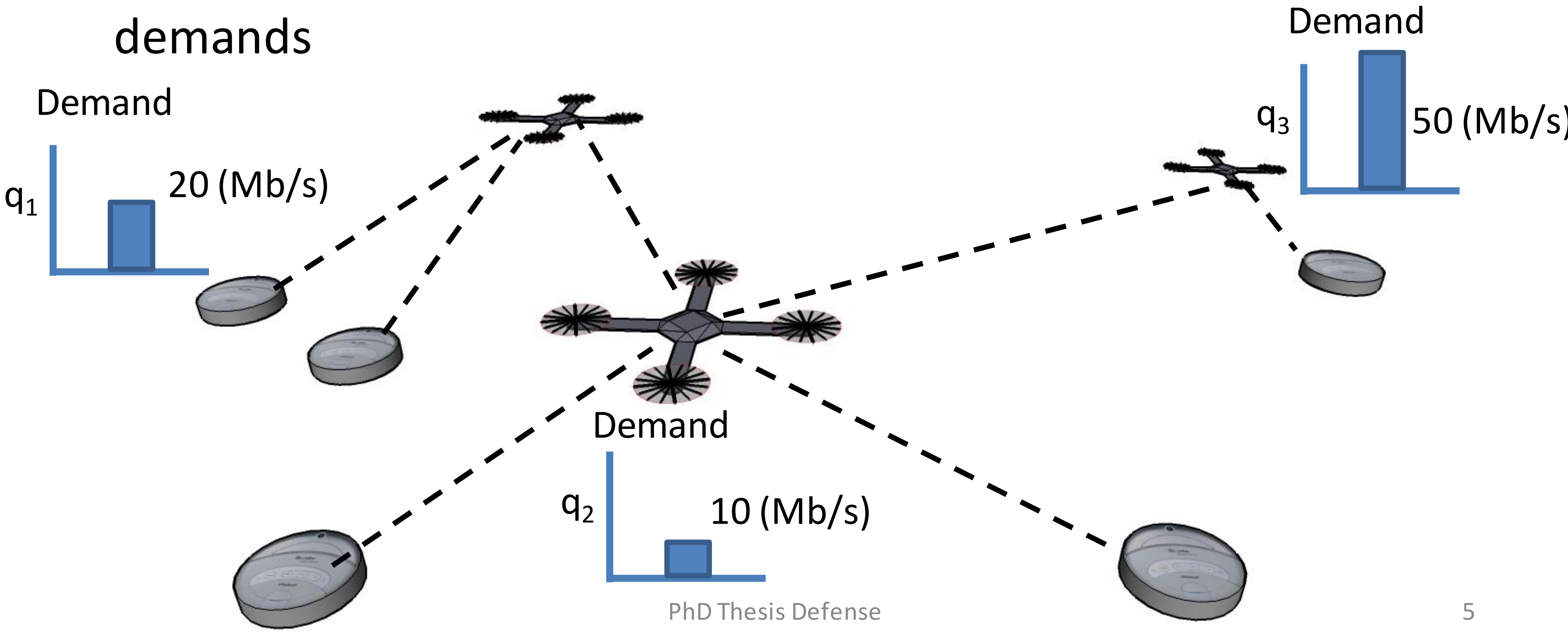
Photo Credit: IEEE Spectrum

Photo Credit: IIIT Robotics Reseach

Problem: Communication Coverage

- k controlled robot routers
- n uncontrolled client agents
- q_j communication demand for j^{th} agent
- $\tilde{q}_{ij}$ communication quality for channel (i,j)

Problem: Optimize robotic router positions to satisfy agent demands



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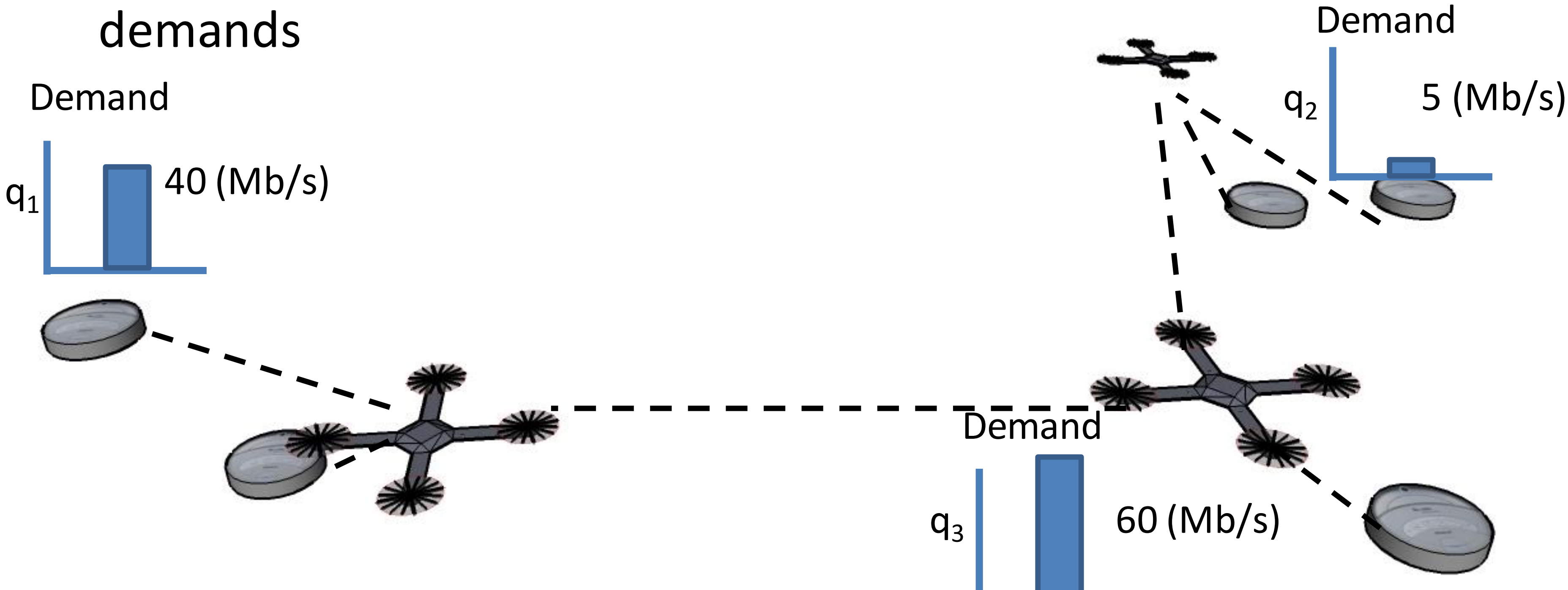
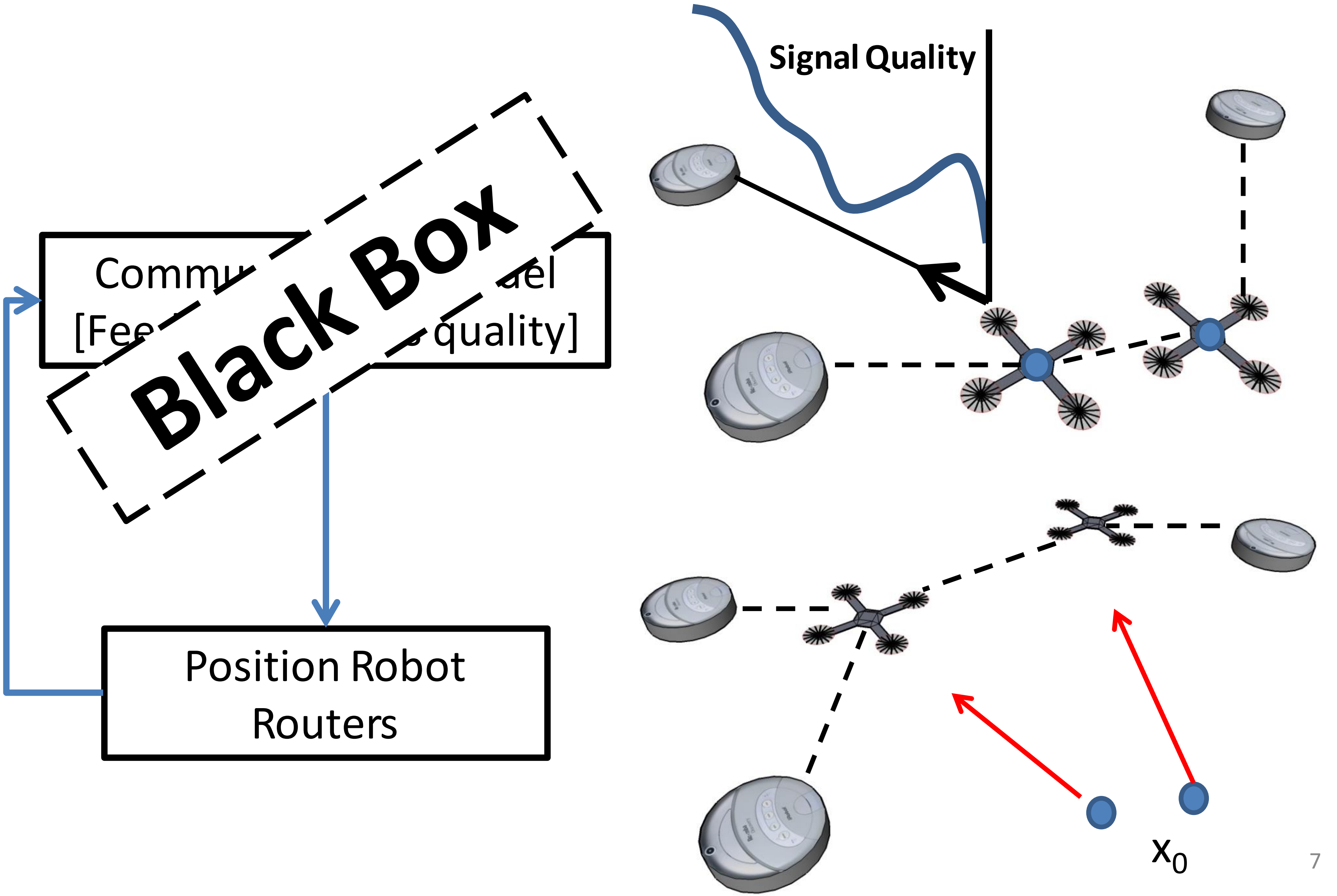


Challenges


Commu
del
[Fee
quality]
Black Box
Position Robot
Routers
Signal Quality
x_0

Related Work: Contextual Overview

Multi-Agent Coordination and Communication

- **Allocation of limited resources** [Tamir et. al. '82, Gonzalez '85 , Vazirani '02, Frazzoli et al. '09]
- **Graph theory and connectivity maintenance** [Lynch et. al. '06 , Jadbabaie '06, Pappas et. al. '09, Cortes '09, Mesbahi et. al. '10]
- **Distributed coverage** [Bullo '04, Bullo et. al. '07, Schwager et. al. '09]

Communication Coverage with Real World Constraints

Realistic Communication Constrained Coordination

- **Stochastic Sampling Methods** [Johansson et. al '07, Le Ny et. al. '12, Sukhatme et. al. '13]
- **Wireless RSS Mapping of Environment** [Sadler et. al. '12, Sadler et. al. '13]
- **Spatial Prediction using Models** [Mostofi et. al. '12, Mostofi et. al. '13, Kumar et. al. '13]

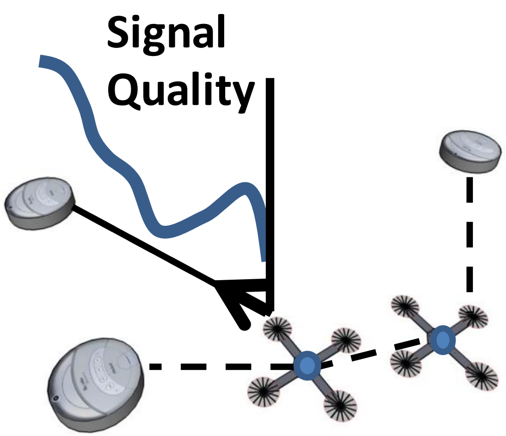
Uncertainty and Real World Performance

- **Uncontrolled disturbances** [Bertsekas '71, Bertsekas '72, Tomlin et. al. '11, Karaman and Frazzoli '12]
- **Scalability to large number of clients** [Gonzalez '85, Mazumdar et. al. '03, Varadarajan et. al. '05, Feldman et. al. '07]
- **Unknown Maps and Environment-independent communication** [Buckley et. al. '88, Schmidt '86, Fitch '88, Roy et. al. '09]

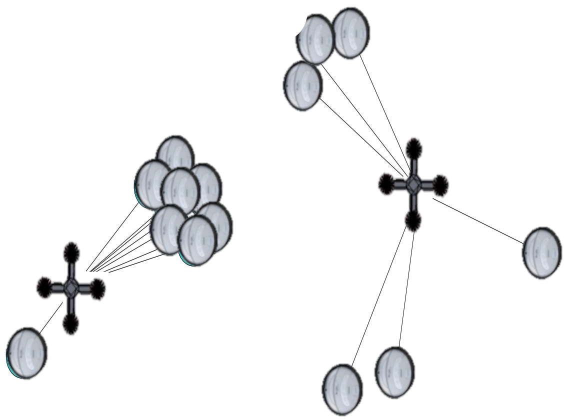
Focus of the Thesis

Solve the communication coverage problem by controlling the position of robot routers using realistic communication models

Realistic communication



Scalable solution



General environments

Photo Credit: IEEE Spectrum

Thesis Contributions in a Nutshell

Optimal Comm Coverage for Large Mobile Teams

Locally Optimal (Distributed) Comm Coverage

Realistic Communication Coverage

Problem Formulation: Optimize over dynamics and connectivity

- Router Placement
- Globally optimal allocations for small problem sizes
- Human/robot with real-time repositioning
- Error bound as number of clients increases
- Large networks

Problem Formulation: Physical model interference

- Lyapunov stability to local minima
- Connectivity maintenance
- Robustness to failure
- Comms with infeasible regions
- Complex indoor env.

Channel Feedback: Signal quality directional profile

- Wireless Channel Mapping

Realistic Comms Optimization

- Satisfy real-time client demands
- Comparison to other methods

Legend:

- Theoretical
- Algorithmic
- Experiments

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Thm: Lyapunov stability to local minima

Thm: Connectivity maintanence

Exp: Robustness to failure

Alg: Comms with infeas. regions

Complex indoor env.

Legend:
- Theoretical
- Algorithmic
- Experiments

Outline

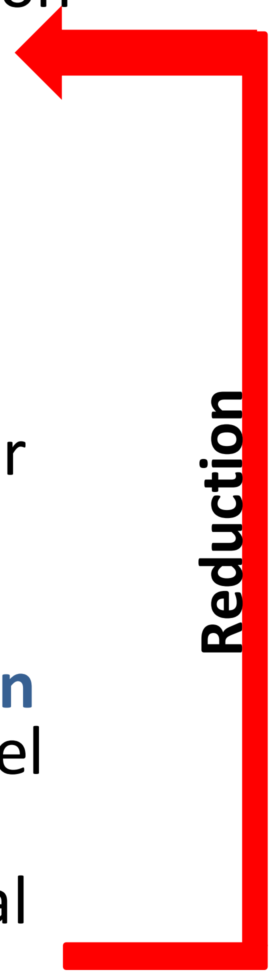
I. Router Placement: Problem formulation and algorithm for positioning robots

II. Large Systems: Algorithm for efficient computation

III. Real Communication: New method for measuring directional information

IV. Realistic Communication Optimization Problem: New model that uses channel feedback

– Satisfy client agent demands in actual implementations



Outline

I. Router Placement: Problem formulation and algorithm for positioning robots

i. Formulation

ii. Handle mobility of clients

iii. Algorithm for finding robot router positions

Assumptions

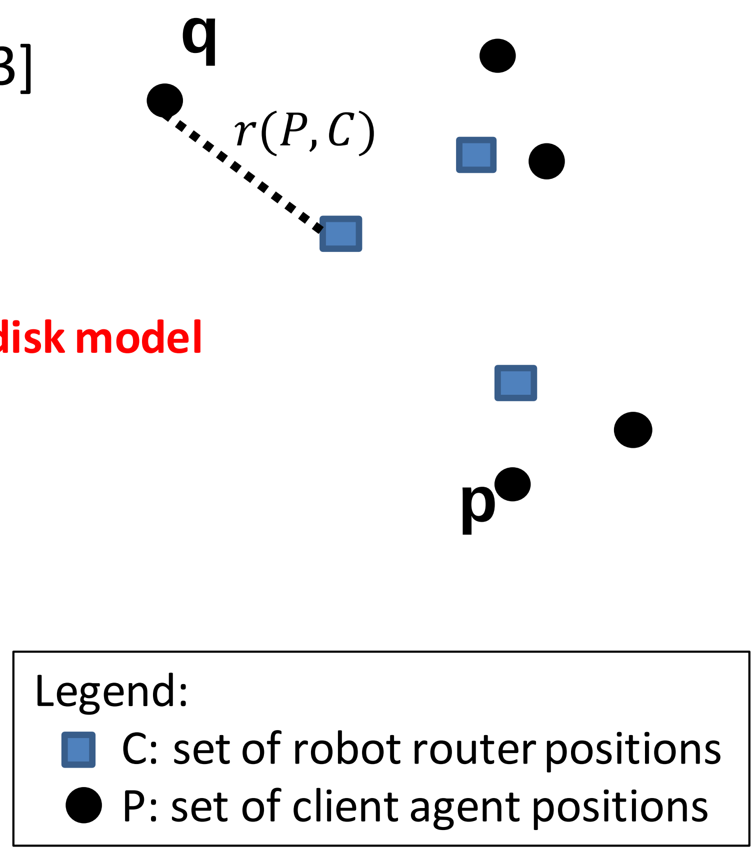
1. Euclidean Disk Model
2. Equal demands
3. Client position known

Approach: Center Placement

- **k-center problem:** Minimize maximum client distance [Gonzalez '85, Vazirani '03]

$$C^* = \text{arg}min_C \; r(P,C)$$
$$r(P,C) = \max_{p \in P} \min_{c \in C} \text{dist}(p,c)$$
$$dist(p,c) = \sqrt{(p-c)^T(p-c)}$$

Euclidean disk model



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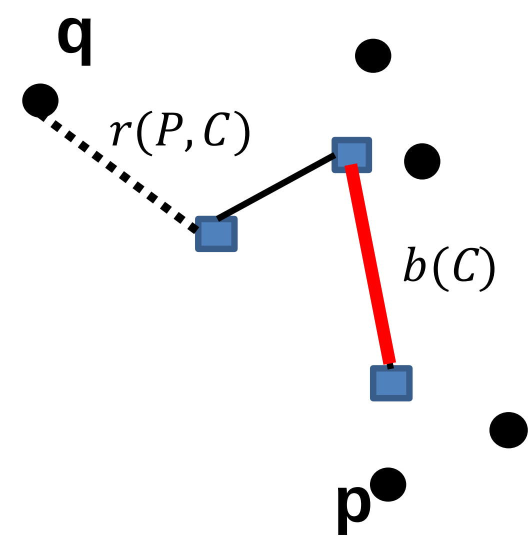

- **Connected k-center problem:** Minimize router-router distance [Gil, Feldman, Rus '12]

$$C^* = \text{argmin}_C \left\{ \max \left(r(P, C), \underline{b(C)} \right) \right\}$$

$$b(C) = \min_{\{(c_i, c_j) \in T\}} dist(c_i, c_j)$$

Legend:
- C: set of robot router positions
- P: set of client agent positions

Approach: Router Placement

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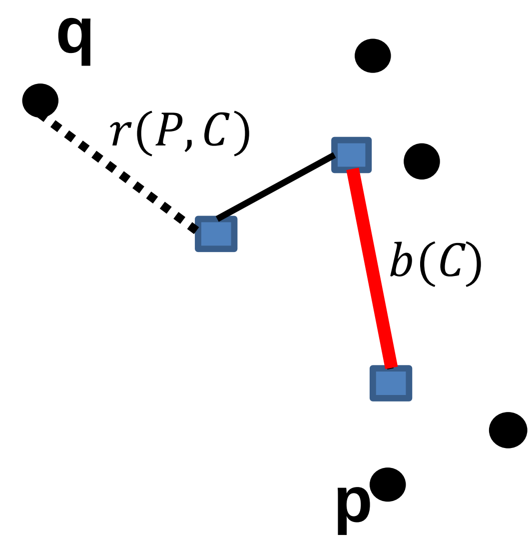

Legend:
C: set of robot router positions
P: set of client agent positions

Intuition: *Seek a fair solution, maximize the weakest link*

Approach: Router Placement

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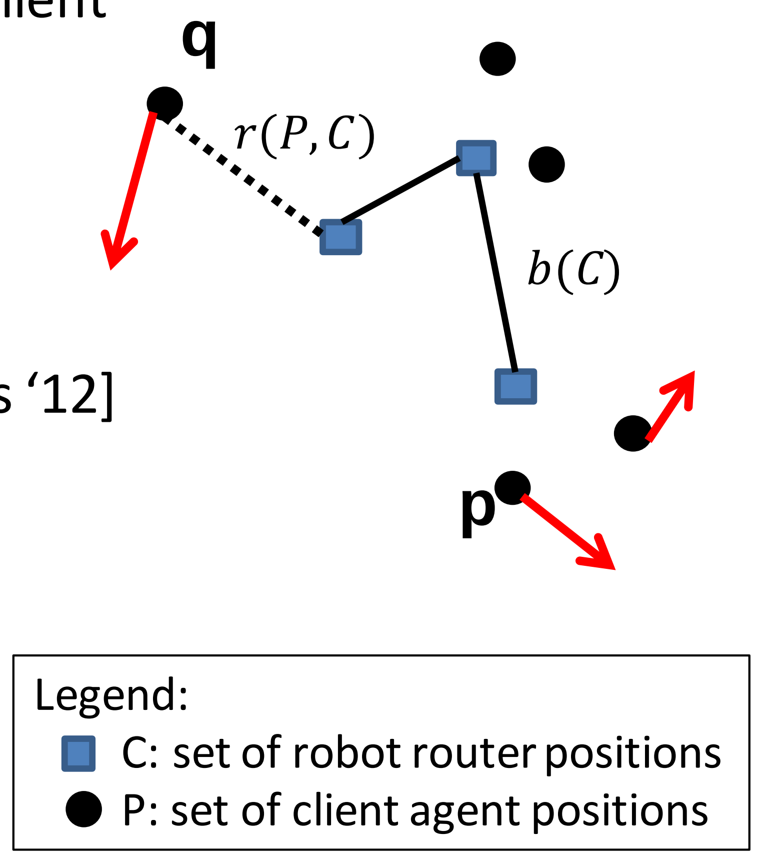
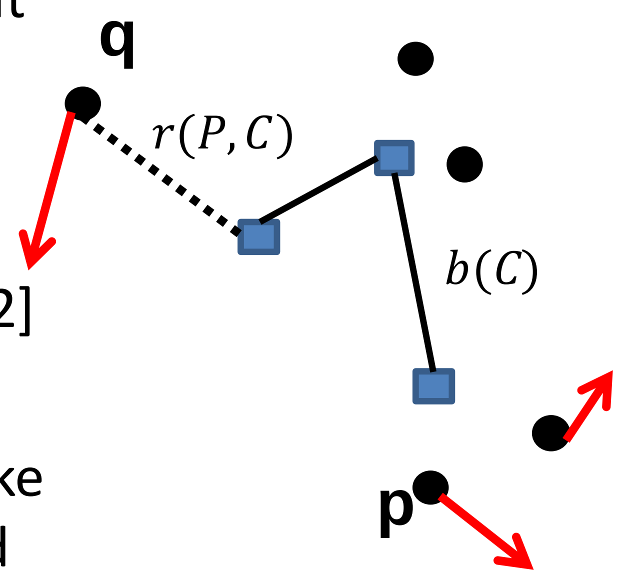
- **Connected k-center problem:** Minimize router-router distance [Gil, Feldman, Rus '12]

- Client agents Move?



Approach: Router Placement

- **k-center problem:** Minimize maximum client distance [Gonzalez ‘85, Vazirani ‘03]
- **Connected k-center problem:** Minimize router-router distance [Gil, Feldman, Rus ‘12]
- **Reachable connected k-center problem:** take into account unknown client movement and control limitations [Gil, Feldman, Rus ’12]



$$p_{\{t+1\}} = p_t + w_t \qquad ||w_t|| \le v_p$$

$$c_{\{t+1\}} = c_t + u_t \qquad ||u_t|| \le v_c$$

Legend:

- C: set of robot router positions
- P: set of client agent positions

Approach: Router Placement

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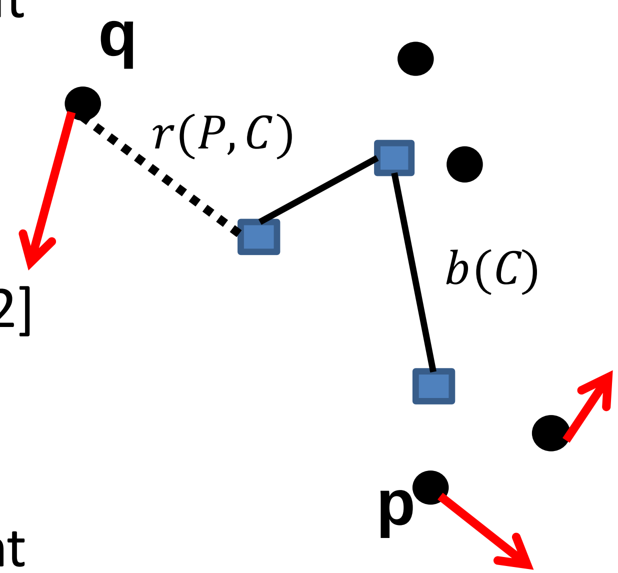


Legend:
C: set of robot router positions
P: set of client agent positions

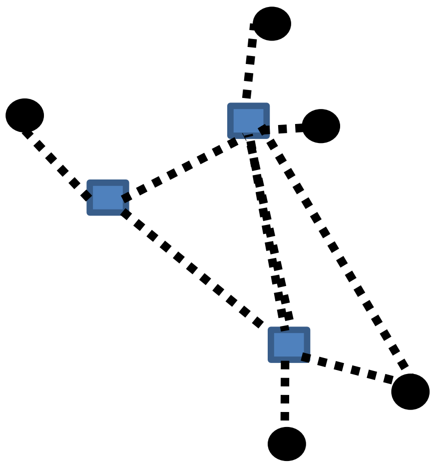
Intuition: Reachability of connected configuration bounded but unknown disturbances [Bertsekas ‘71, Rakovic ‘09]

Result: Exact Algorithm

Theorem: Our algorithm provides exact solution to reachable connected k-centers problem. If feasible, a configuration of routers, C, provides a connected configuration for a minimum of t seconds

"Communication Coverage for Independently Moving Robots" *Gil, Feldman, Rus, IROS 2012*

- Convex program for optimizing connected k-centers and reachability



- Expensive: $n^{O(k)}$

Contributions Outline

I. **Router Placement:** Problem formulation and algorithm for positioning routers

II. **Large Systems:** Algorithm for efficient computation

III. **Real Communication:** New method for measuring directional information

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   - Satisfy client demands in actual implementations

Assumptions
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Contributions Outline

Assumptions

1. Euclidean Disk Model
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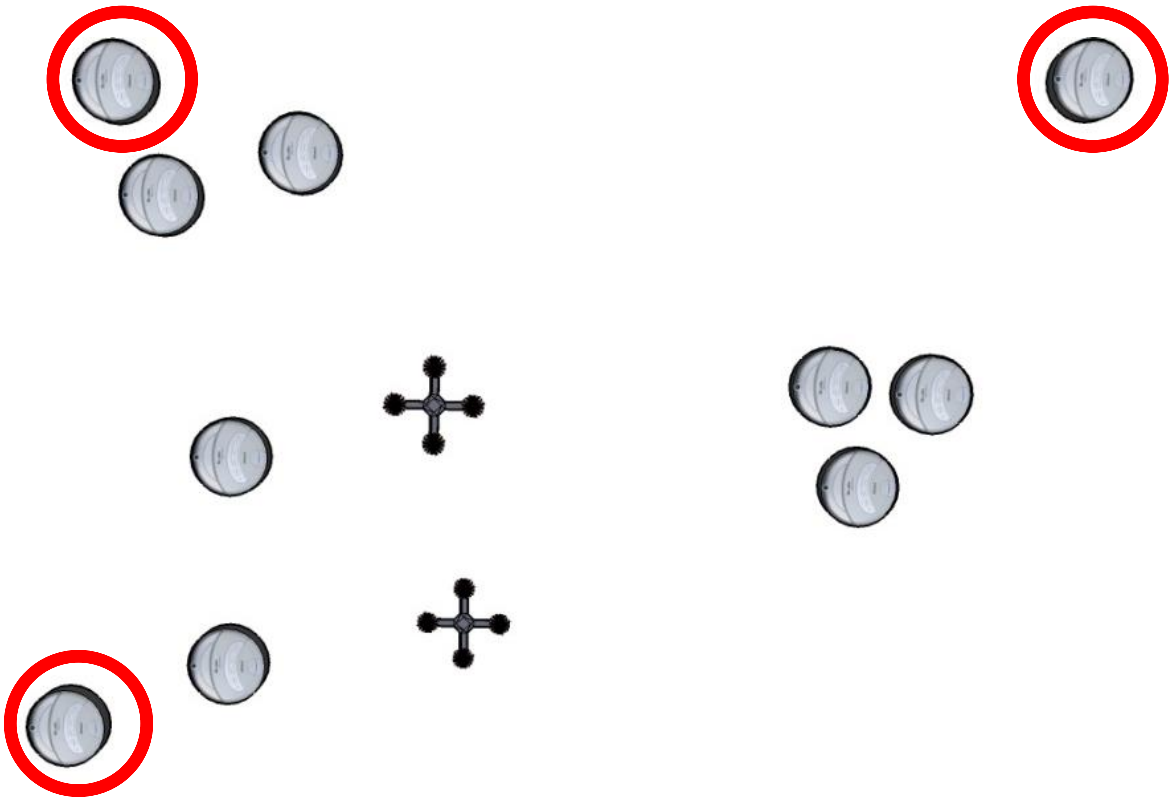
II. Large Systems: Algorithm for efficient computation

i. Find a bounded error solution for static clients

ii. Find a bounded error solution for continuously moving clients

Efficiency: Compression of Input Points

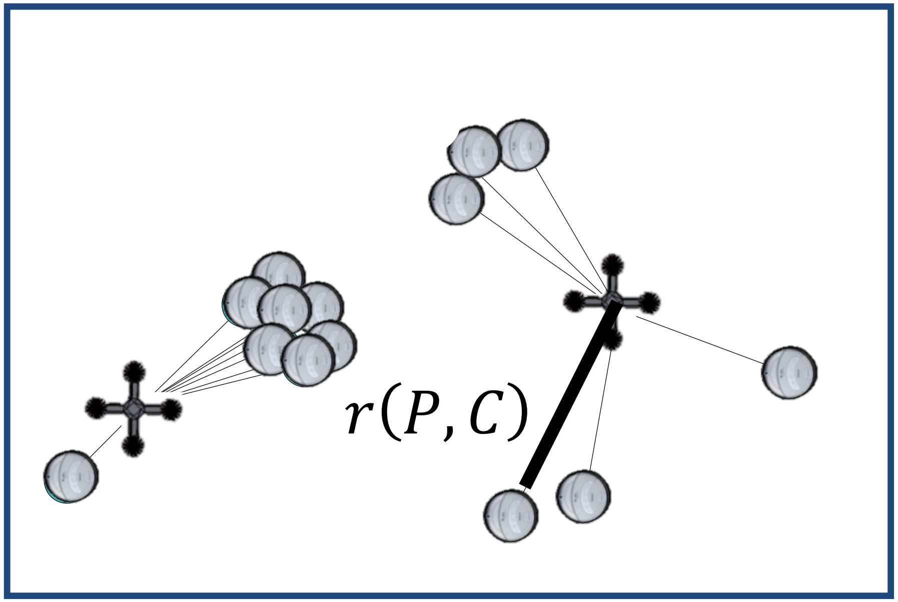
Compute solution of a carefully chosen subset S

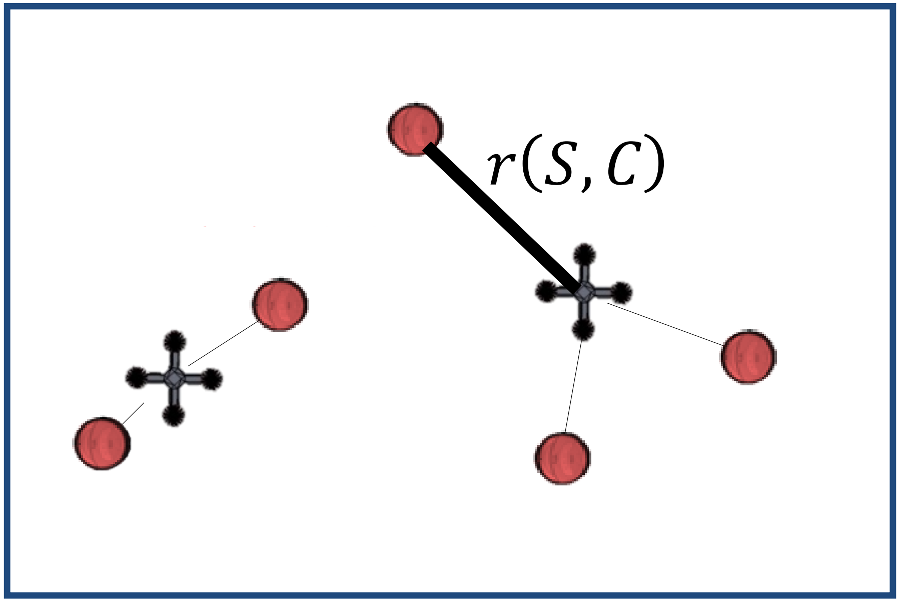


Efficiency: Compression of Input Points

Property: For $\epsilon > 0$ a set S is a (k, ϵ)-coreset for the input set P if for every C, |C|=k

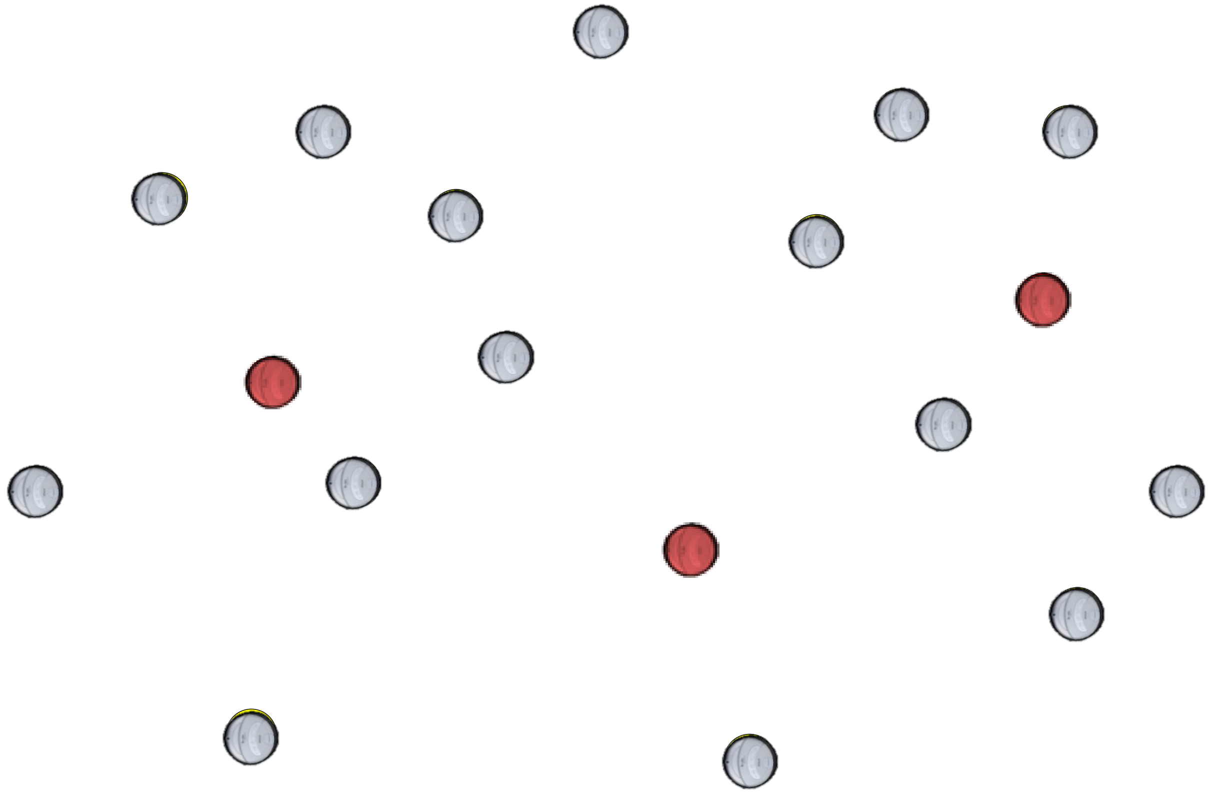
$$r(S, C) \leq r(P, C) \leq (1 + \epsilon) r(S, C)$$





A Coreset Construction

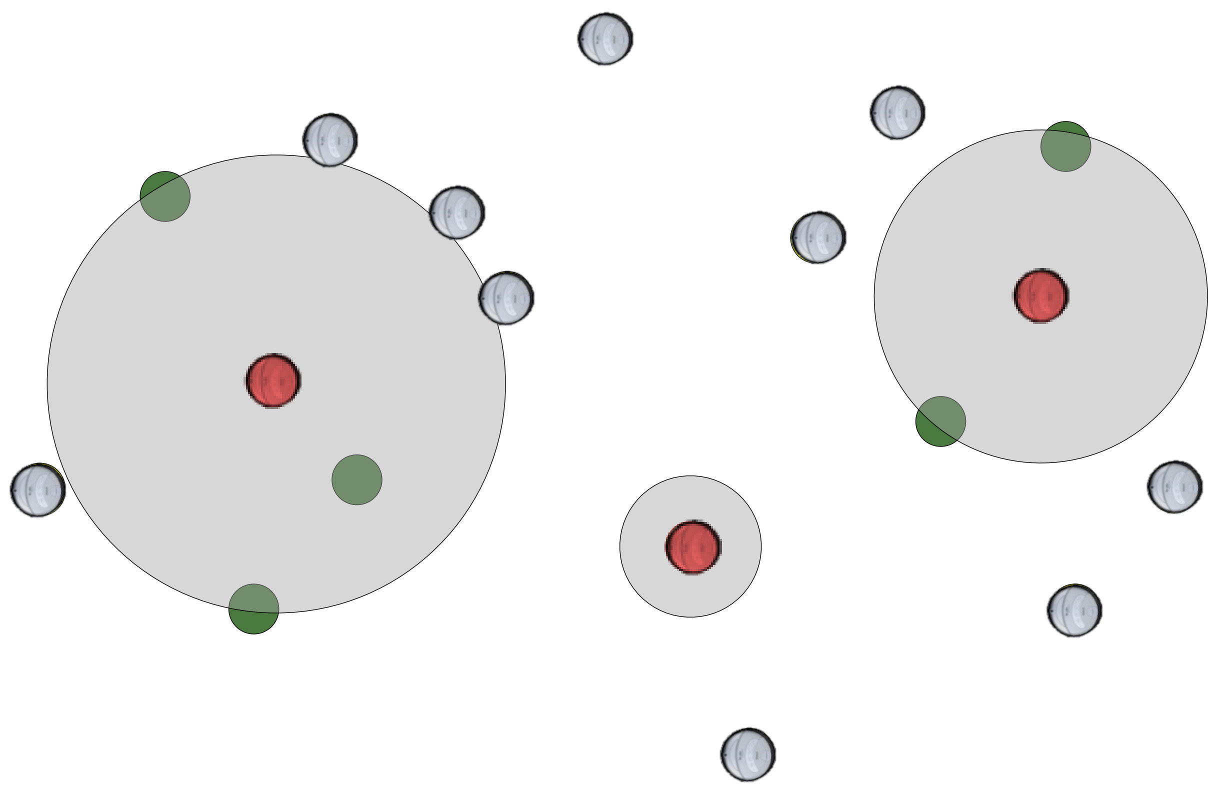
- Randomly sample a small number of clients



First Iteration

A Coreset Construction

- Remove half of the closest clients to the selected representatives



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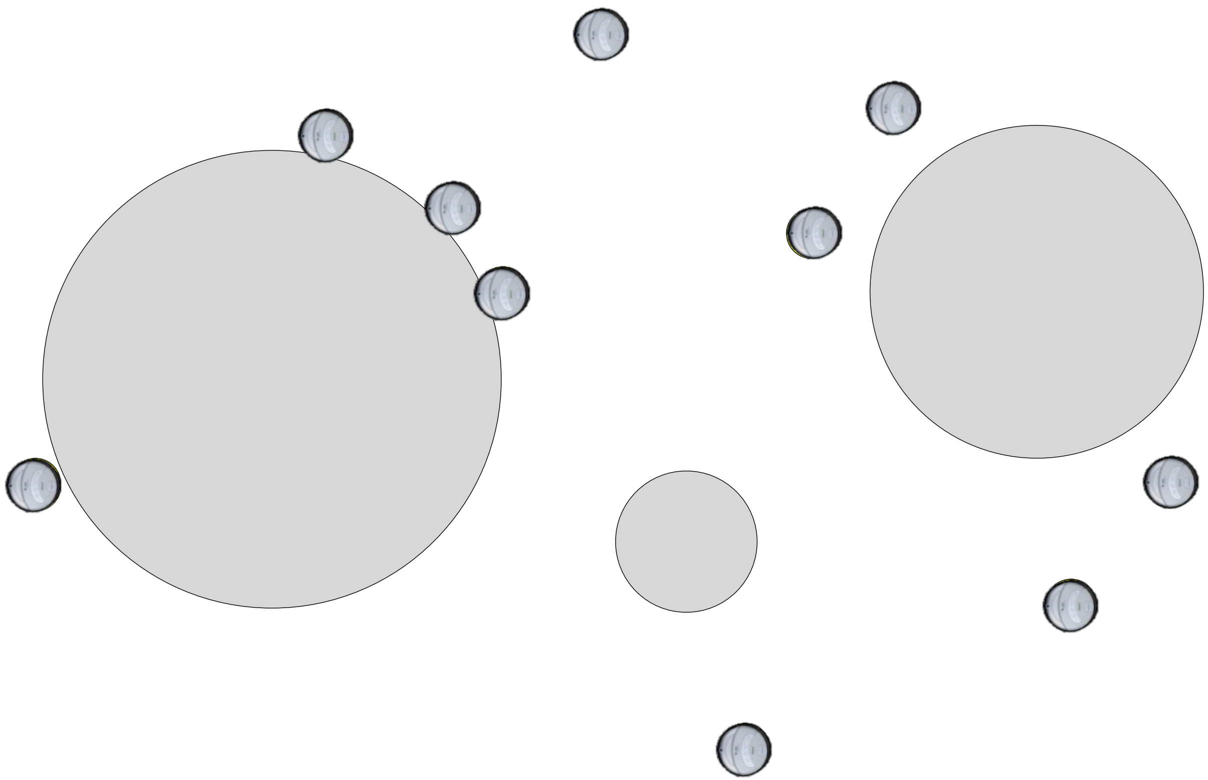
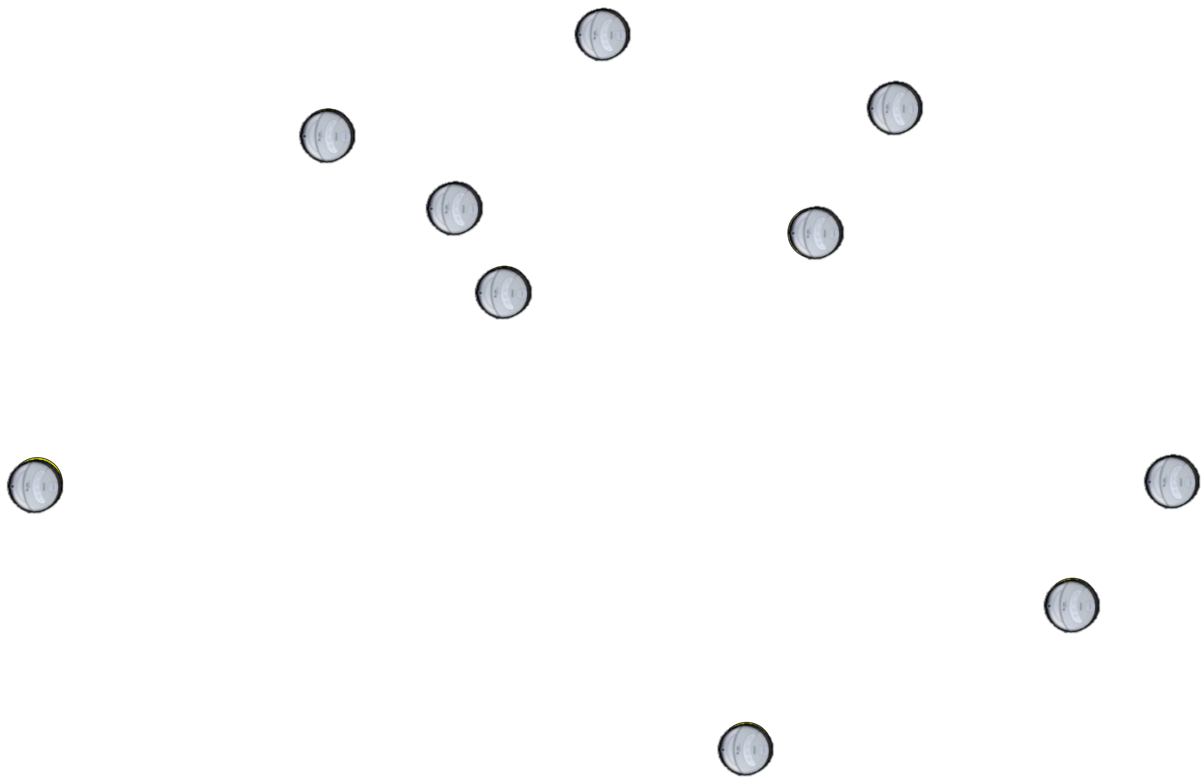


First Iteration

A Coreset Construction

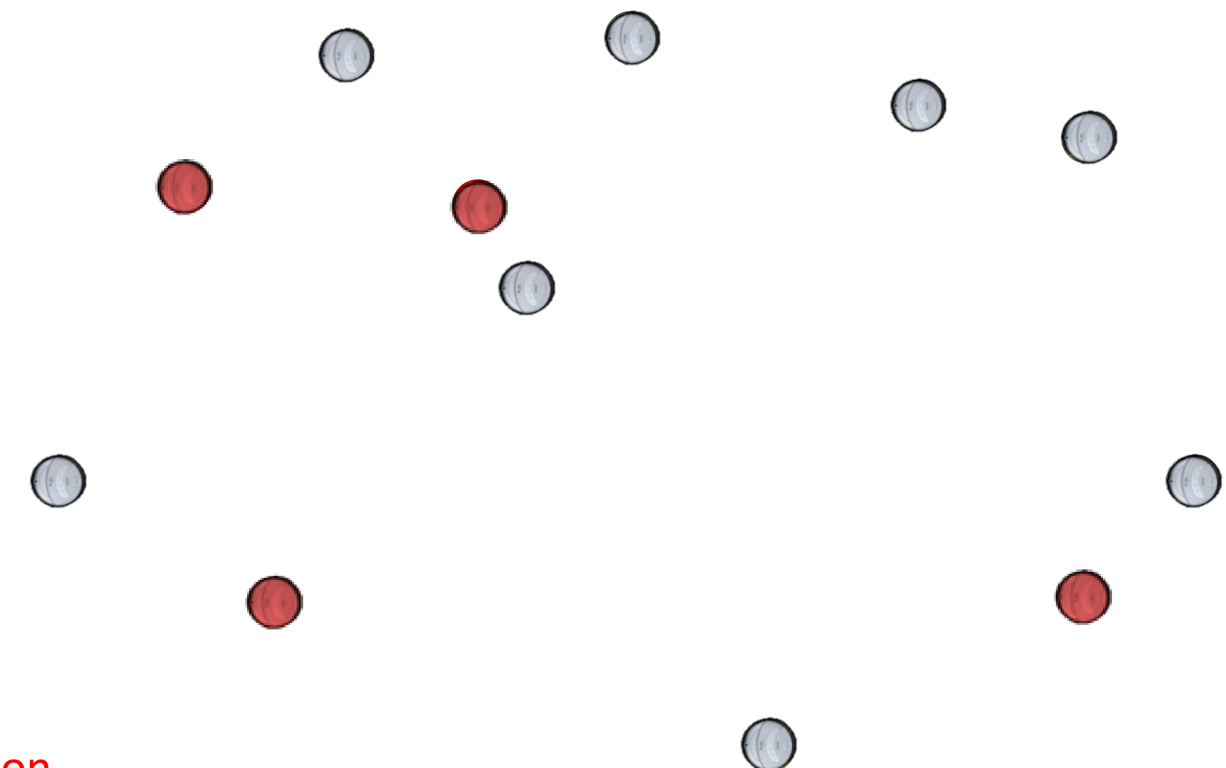
- Repeat procedure on remaining clients



Second Iteration

A Coreset Construction

- Repeat procedure on remaining clients



Second Iteration

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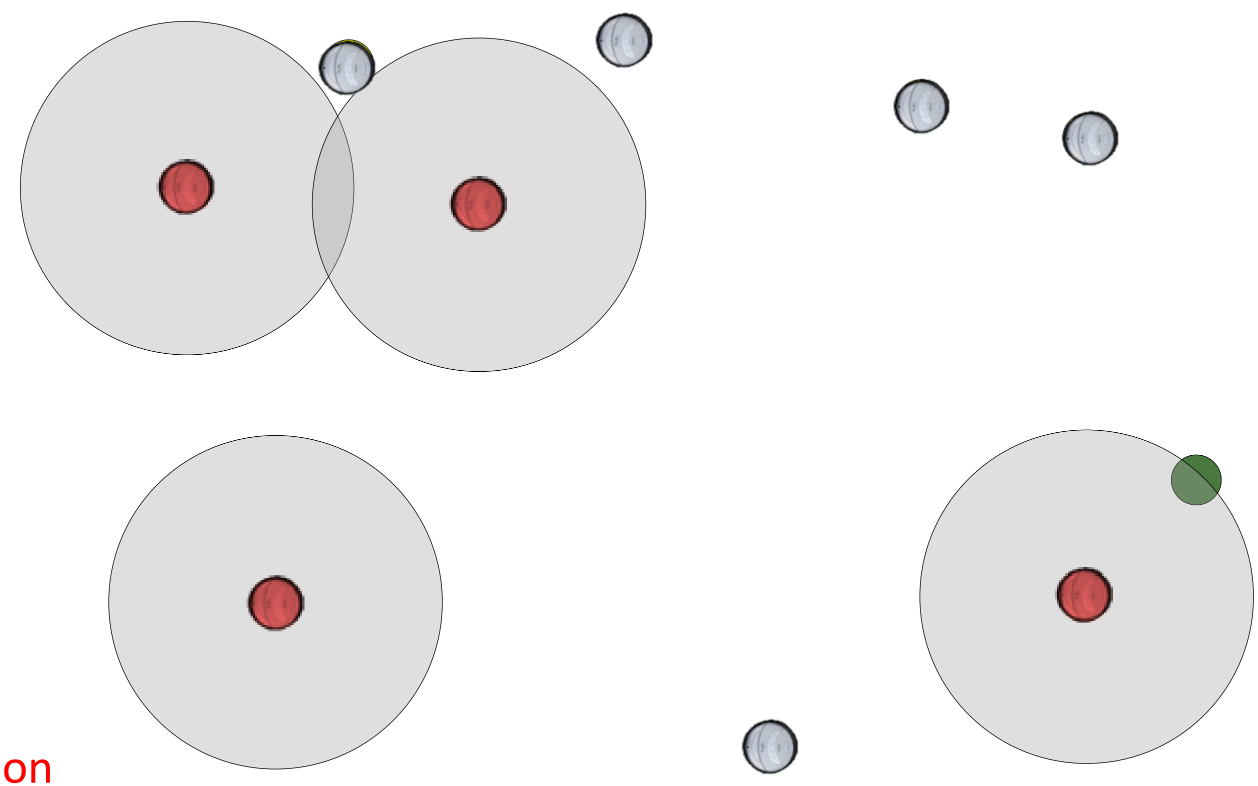

Second Iteration

A Coreset Construction

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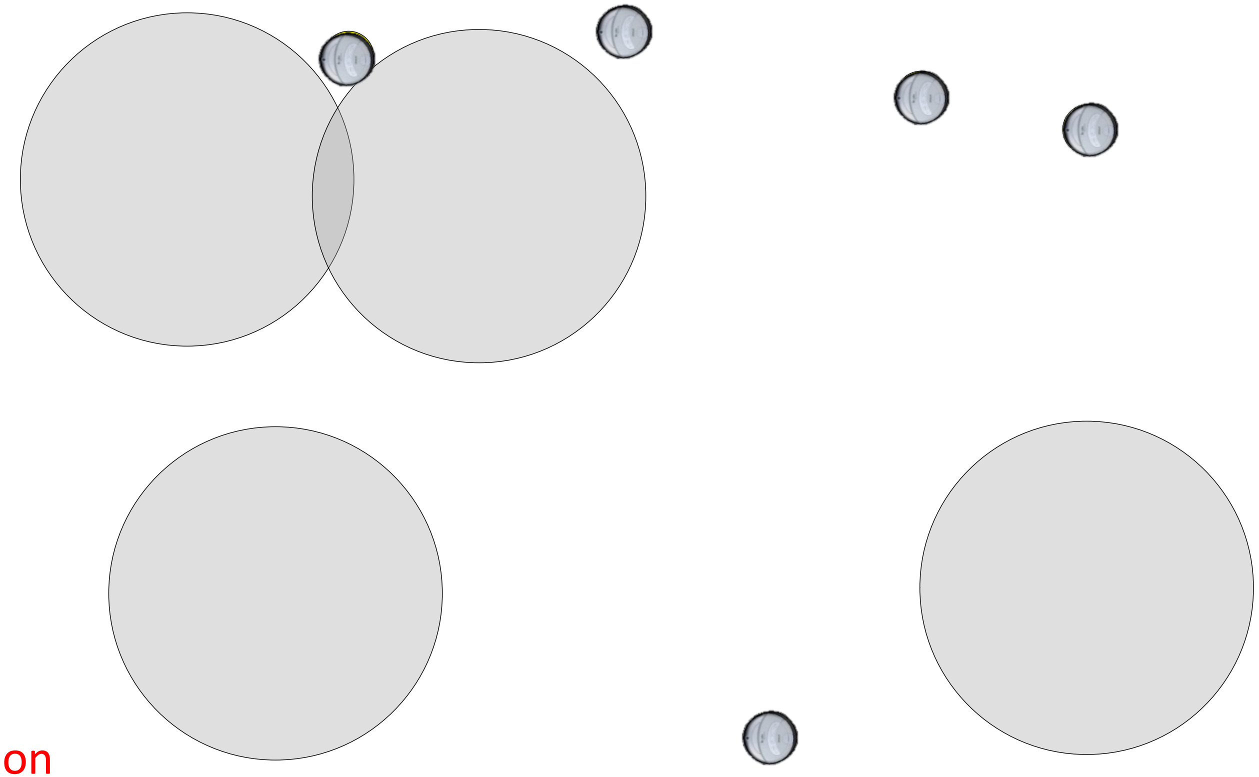
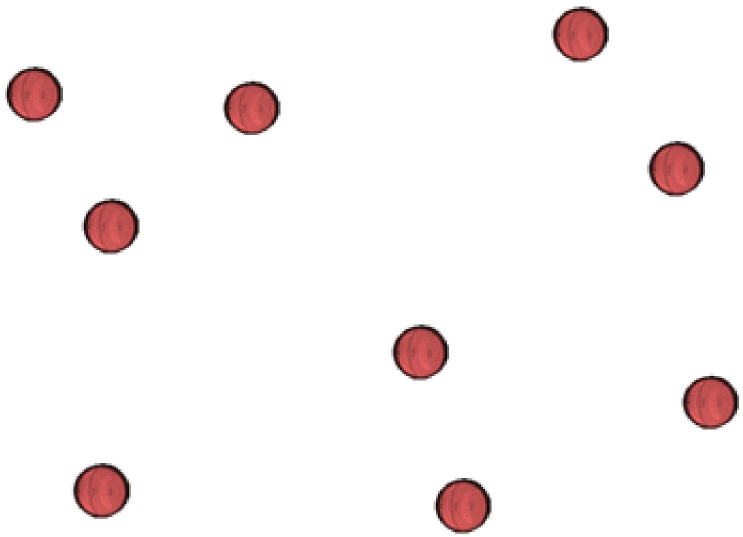


Second Iteration

A Coreset Construction

- Repeat procedure until all clients are represented
- Return coreset S



Final Iteration

Efficiency: Compression of Input Points

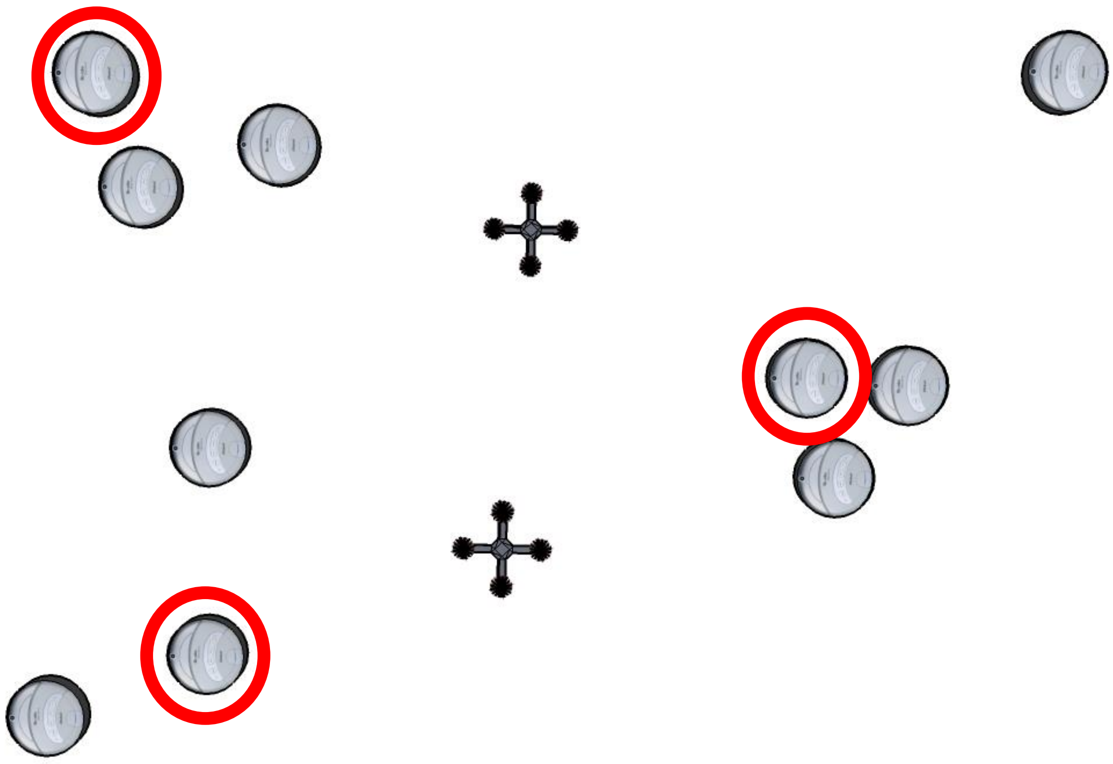
The k-center of S is a (1+ ϵ)- approximation for the k-center of P

[Agarwal and Procopiuc '02, Agarwal and Har-Peled and Varadarajan '05, T. Chan '08]

Theorem: The *reachable connected k-center* of S is a (1+ ϵ)- approximation for the *reachable connected k-center* of P

"Communication Coverage for Independently Moving Robots" *Gil, Feldman, Rus IROS 2012*

Efficiency: Compress Moving Clients

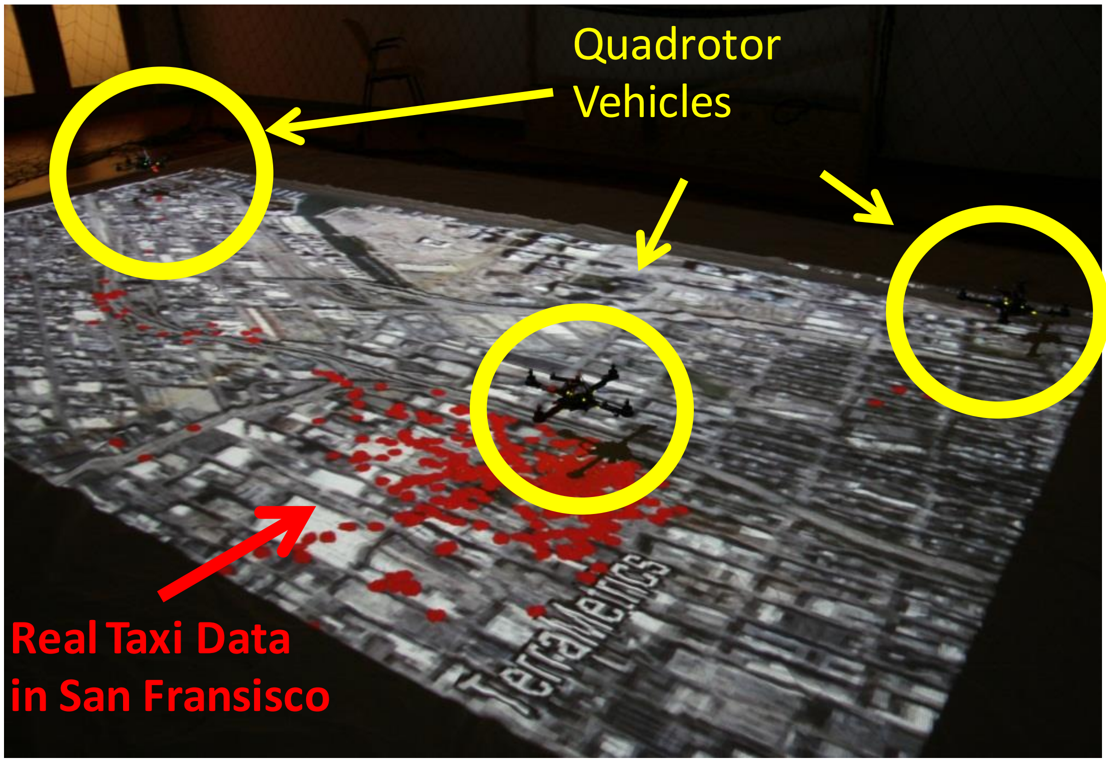


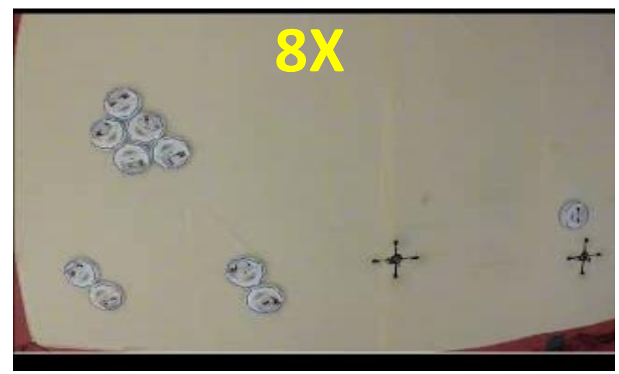
Efficiency: Compressing Moving Points

Theorem: We can maintain a dynamic (k, ε)-coreset S for a moving set P in R^d, *d=2*, using space and update time polynomial in $k \log n / \varepsilon$ where n=|P|, $|S| = \left(\frac{k \log n}{\varepsilon}\right)^{O(1)}$

K-Robots Clustering of Moving Sensors using Coresets: *Feldman, Gil, Julian, Knepper, Rus,* ICRA 2013

Solving for Router Positions in Real Time





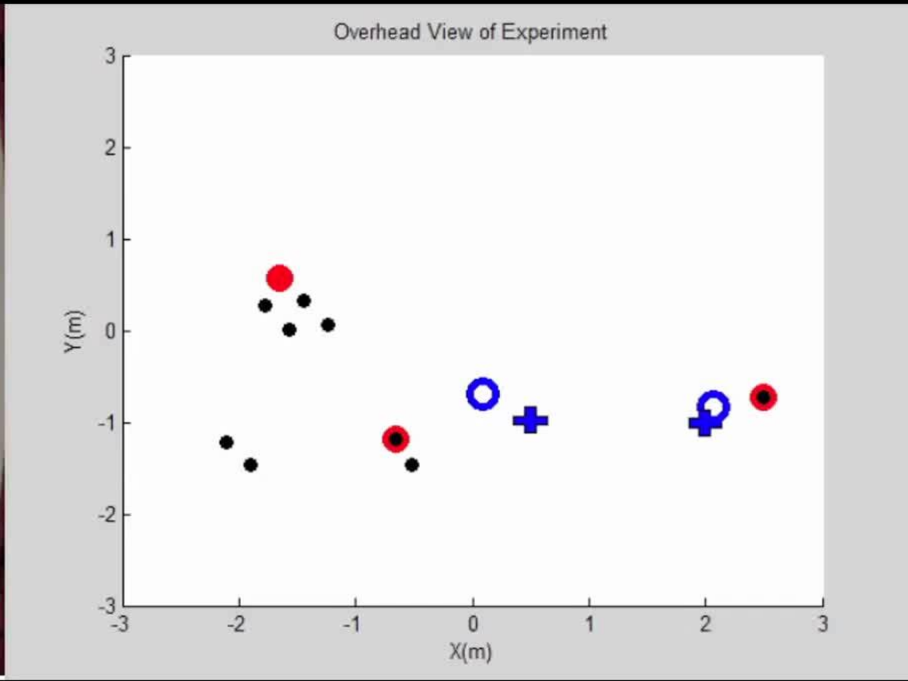
Small Scale: Heterogeneous Team

Setup (2x)

Small Scale: Heterogeneous Team

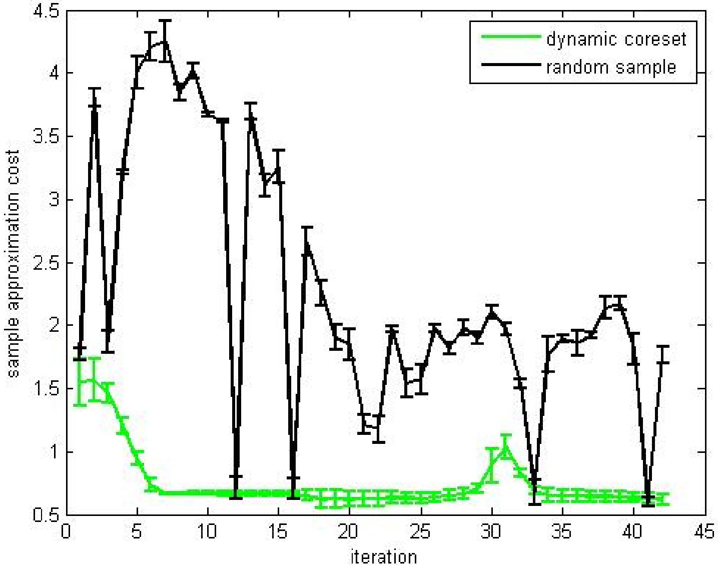
Overhead View (8x)

Matlab GUI View



Small Scale: Heterogeneous Team

Coreset Quality

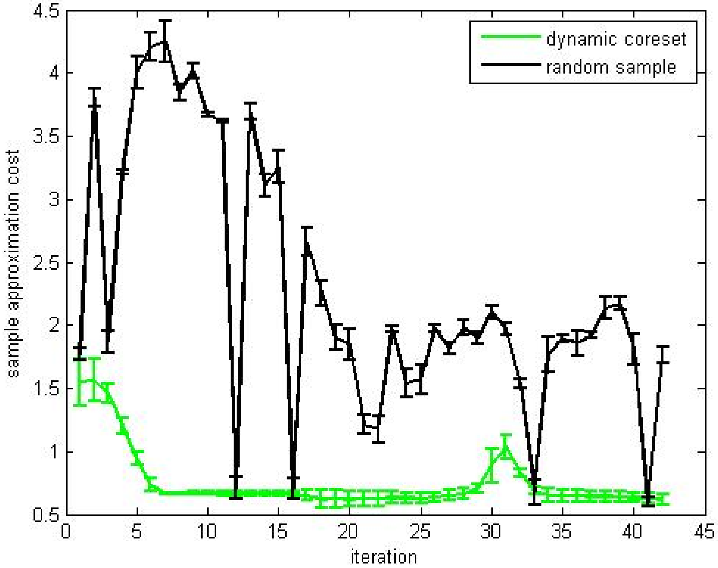


Legend

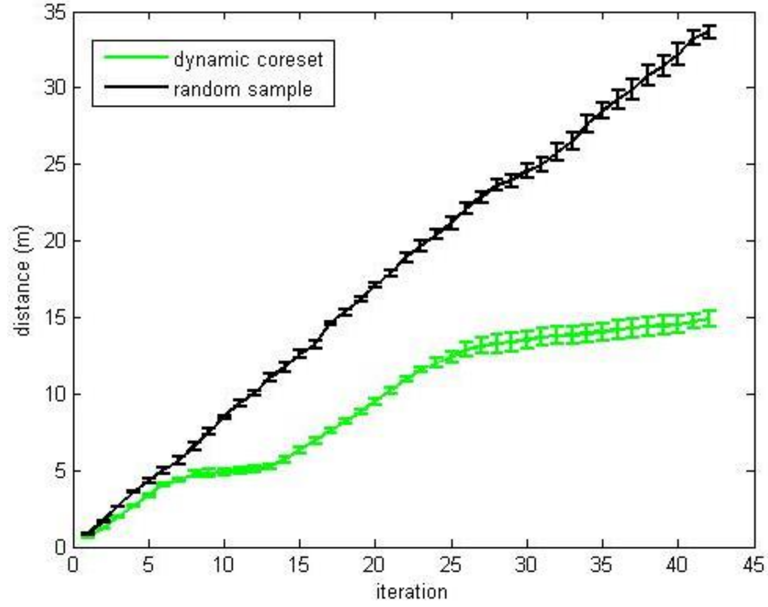
dynamic
random

Small Scale: Heterogeneous Team

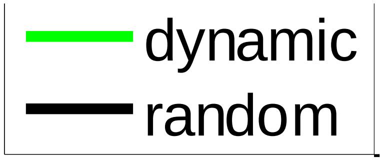
Coreset Quality



Total Distance Traveled



Legend



Small Scale: Heterogeneous Team

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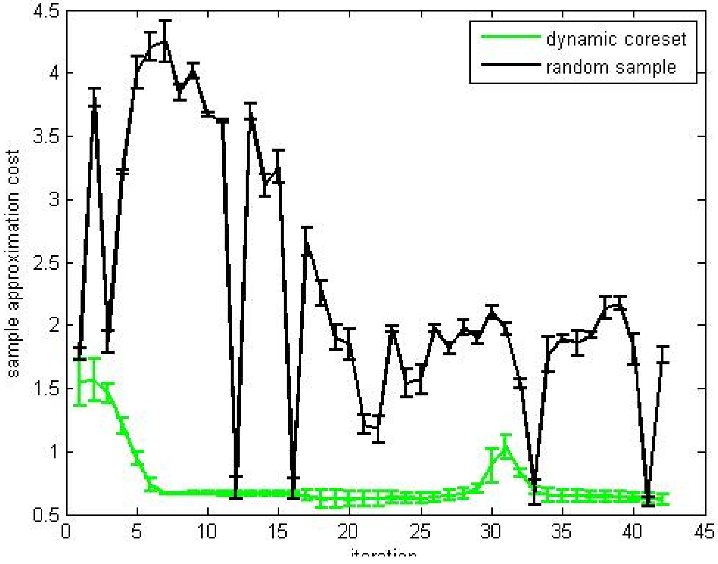

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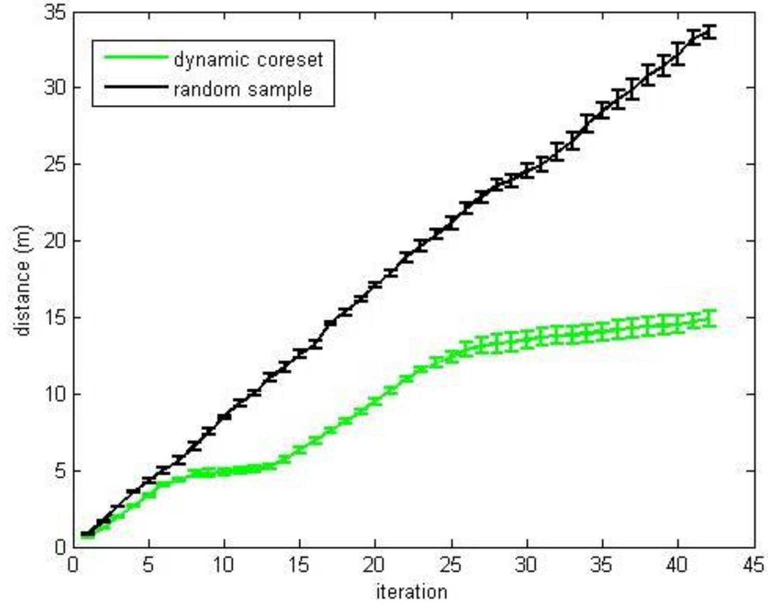
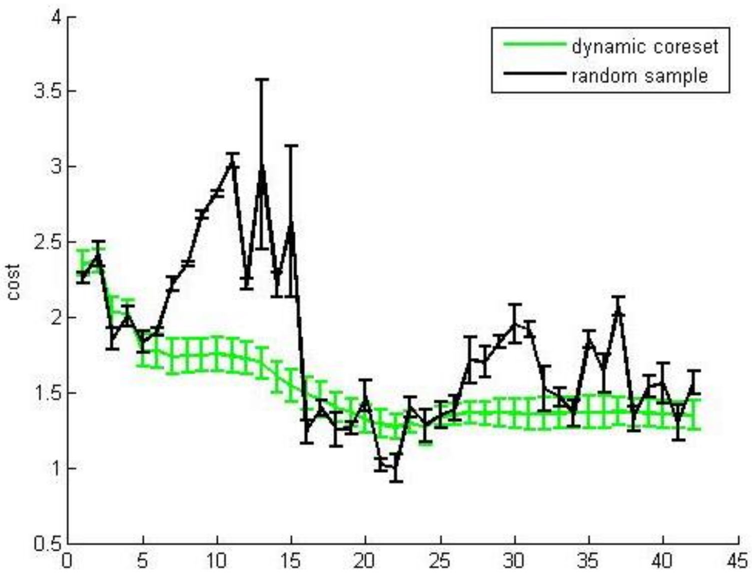
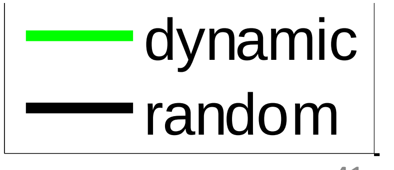


Cost

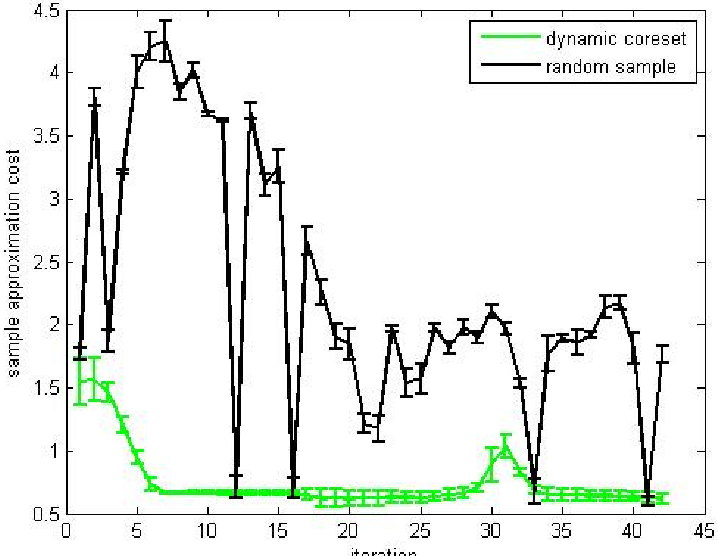


Legend



Small Scale: Heterogeneous Team

Coreset Quality



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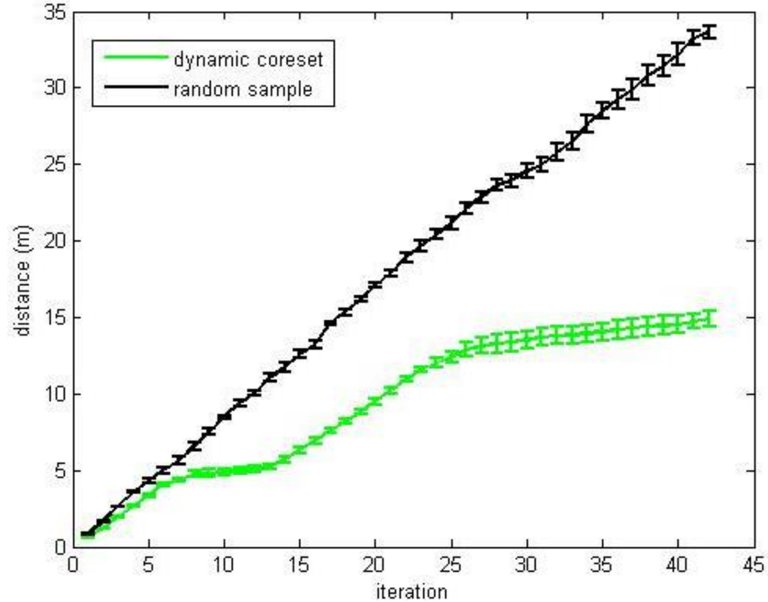
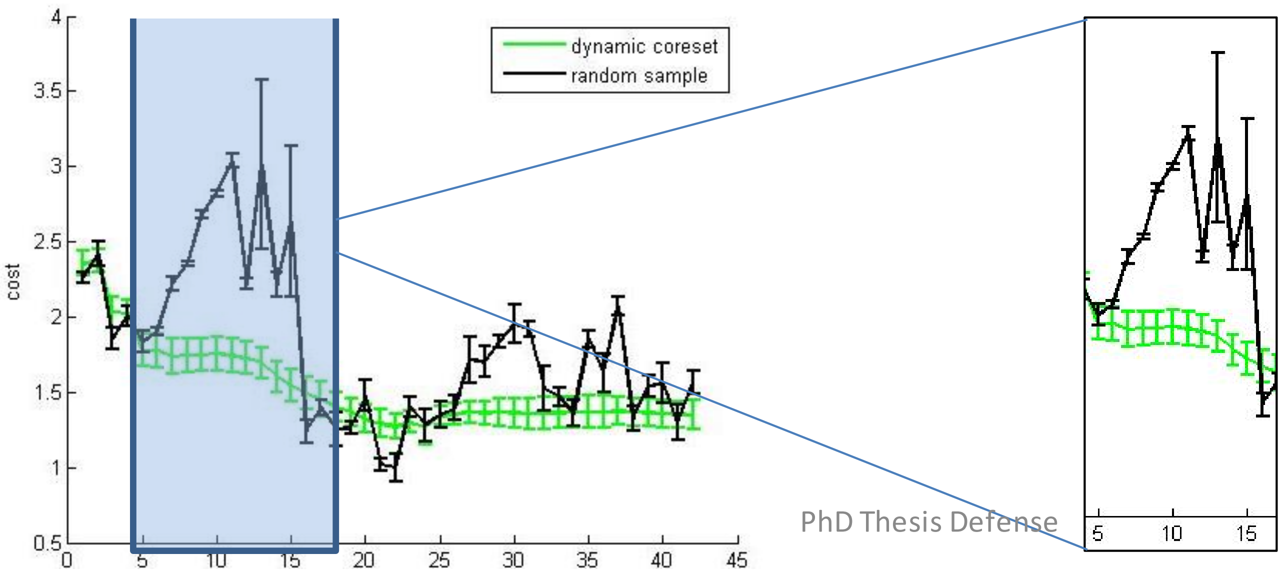
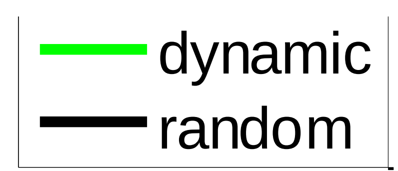


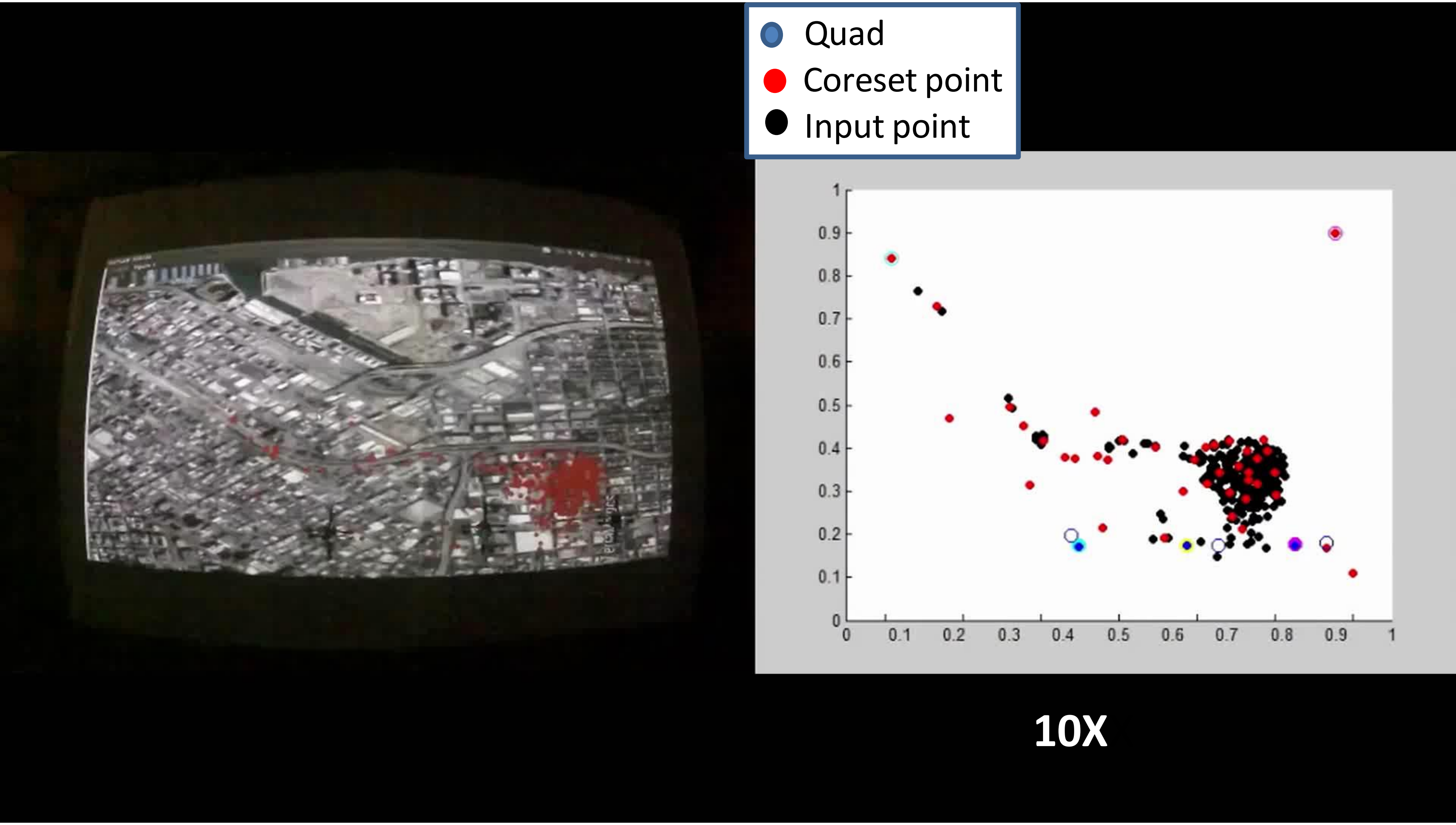
Cost



Legend



Dynamic Coreset: Large Scale Experiment



Real-time taxi data over a period of 10 minutes in San Fransisco, CA

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Problem Formulation: Optimize over dynamics and connectivity

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Human/robot with real-time repositioning

Error bound as number of clients increases

Large networks

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Realistic Communication Coverage

Channel Feedback: Signal quality directional profile

Wireless Channel mapping

Realistic Comms Optimization

Satisfy Real-time client demands

Comparison other methods

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Thm: Lyapunov stability to local minima

Thm: Connectivity maintanence

Exp: Robustness to failure

Alg: Comms with infeas. regions

Exp: GPS-denied indoor env.

Legend:
- Theoretical
- Algorithmic
- Experiments

Using Real-time Channel Feedback

Outline

I. **Router Placement:** Problem formulation and algorithm for positioning routers

Assumptions
1. ~~Euclidean Disk Model~~
2. ~~Equal demands~~
3. ~~Client position known~~

II. **Large Systems:** Algorithm for efficient computation

III. **Real Communication:** New method for measuring directional information

IV. **Realistic Communication Optimization Problem:** New model that uses channel feedback

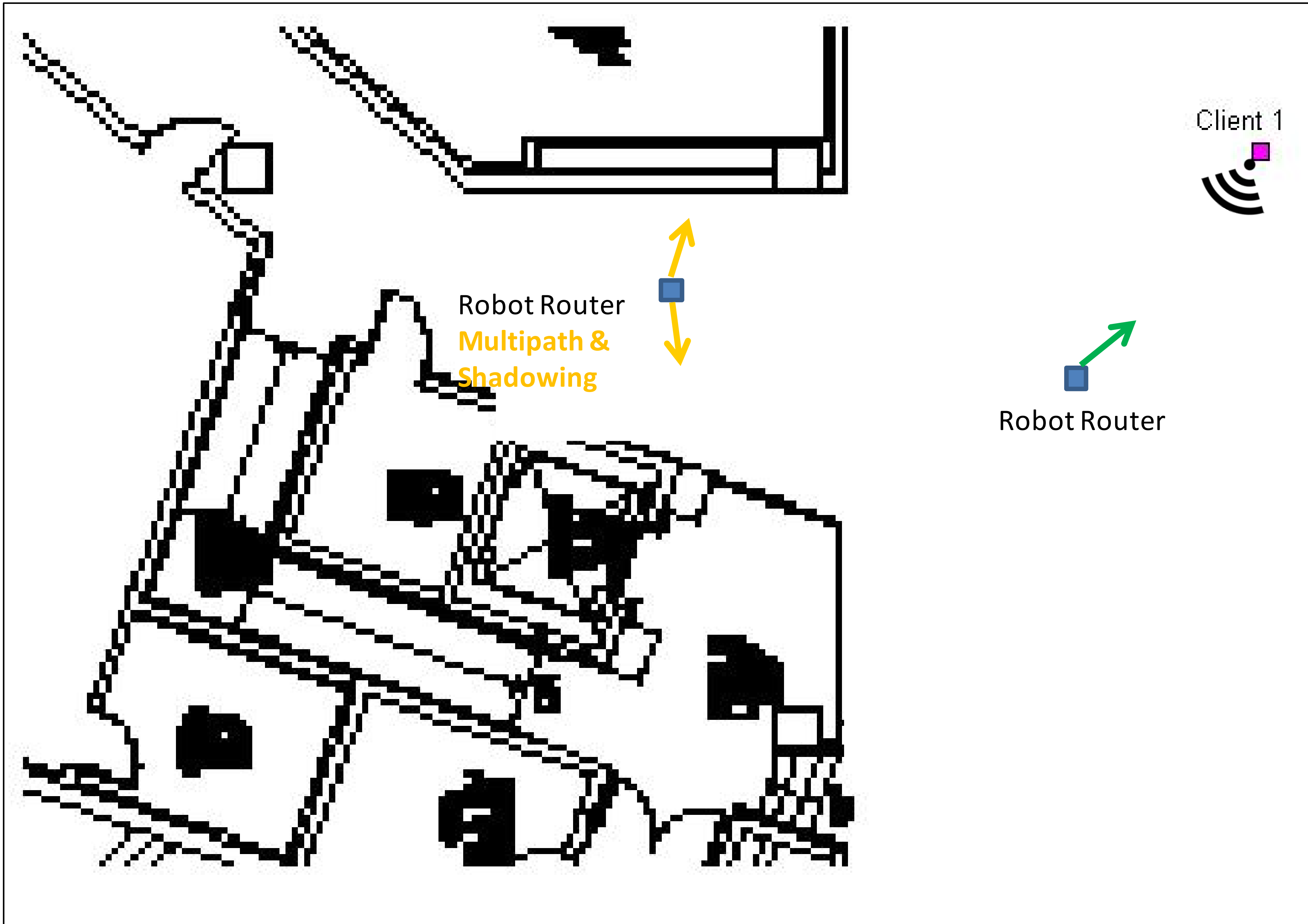
Why is this problem hard?

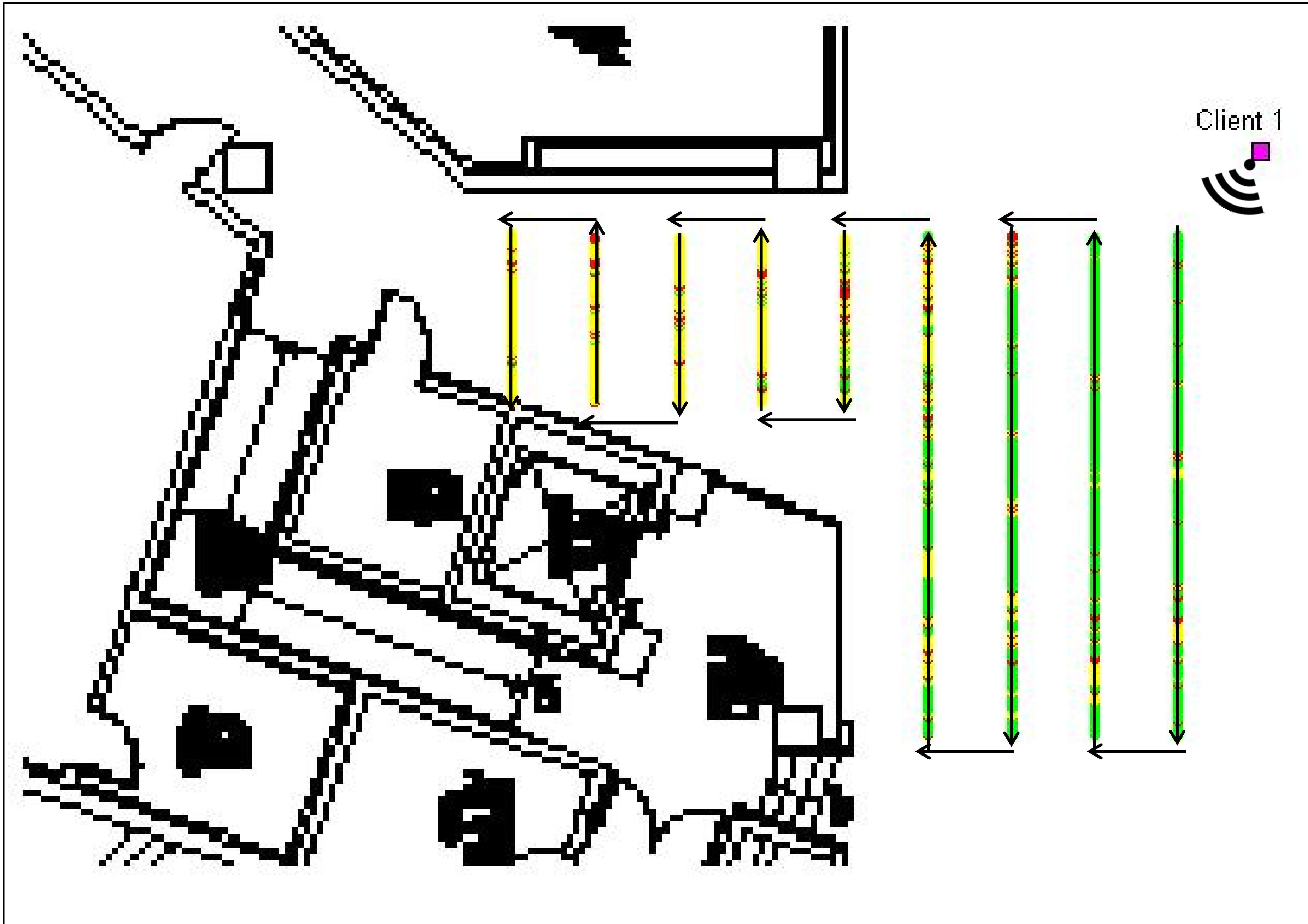
Robotics leverages positional control in R^3

But wifi comms notoriously hard to predict!
[Goldsmith '05, Johansson '07, Mostofi 2012]

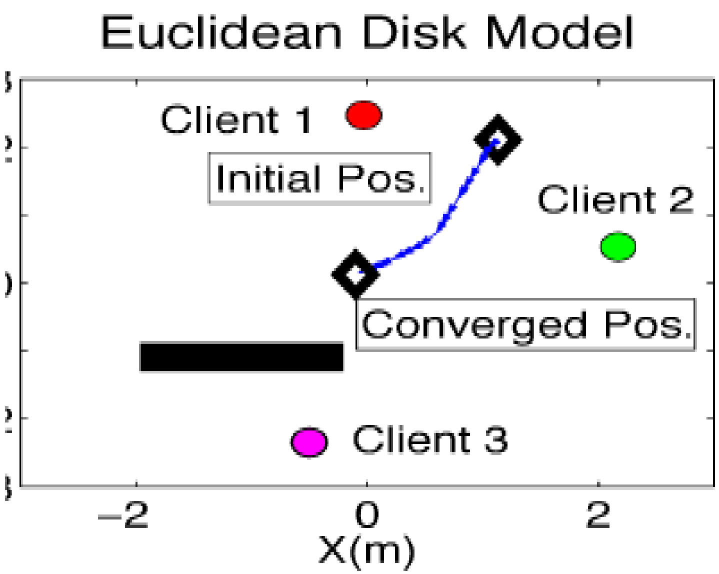
?

How signal quality relates to spatial positioning (different environments)?


Client 1
Robot Router
Multipath &
Shadowing
Robot Router

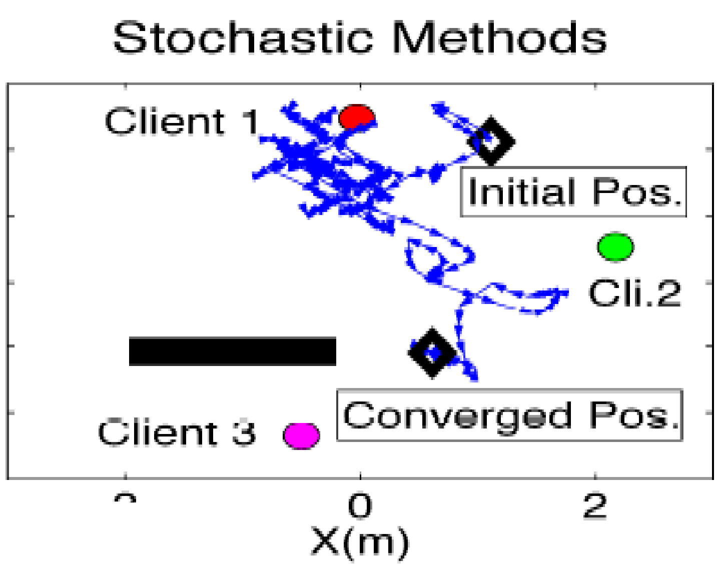

Client 1

Current Methods



Euclidean Disk Model: [Bullo et. al. '04, Jadbabaie et. al. '03, Murray et. al. '07]

- fast convergence
- but converged solution does not meet demands

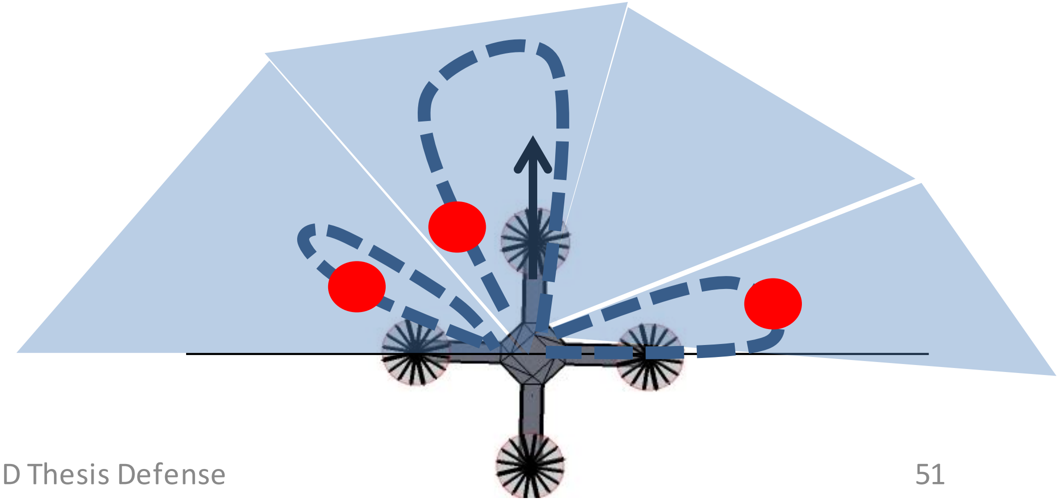


Stochastic Sampling: [Johansson et al. '07, Le Ny et al. '12, Sukhatme et al. '13]

- method meet demands
- but must explore and often suffer in low SNR areas

What can be Improved here?

Prediction? [Mostofi et. al. ’12, Ribiero and Fink et. al. ’13, Mostofi et al. ‘13]



What can be Improved here?

Prediction?

1) Complex models, many distributions to choose from
2) Prohibitive assumptions such as
   - Known environment
   - Static surroundings
   - Known client locations

Assumptions of Standard Spatial Models for Signal Quality

Known environment | Known positions | Known obstacle map | Known distributions

$$\underbrace{L_0 - 10n \cdot \log(\|x_i - x_j\|)}_{\text{Path–loss}} - \underbrace{W(x_i, x_j)}_{\text{Shadowing}} - \underbrace{\mathcal{F}}_{\text{Fading}}$$

What can be Improved here?

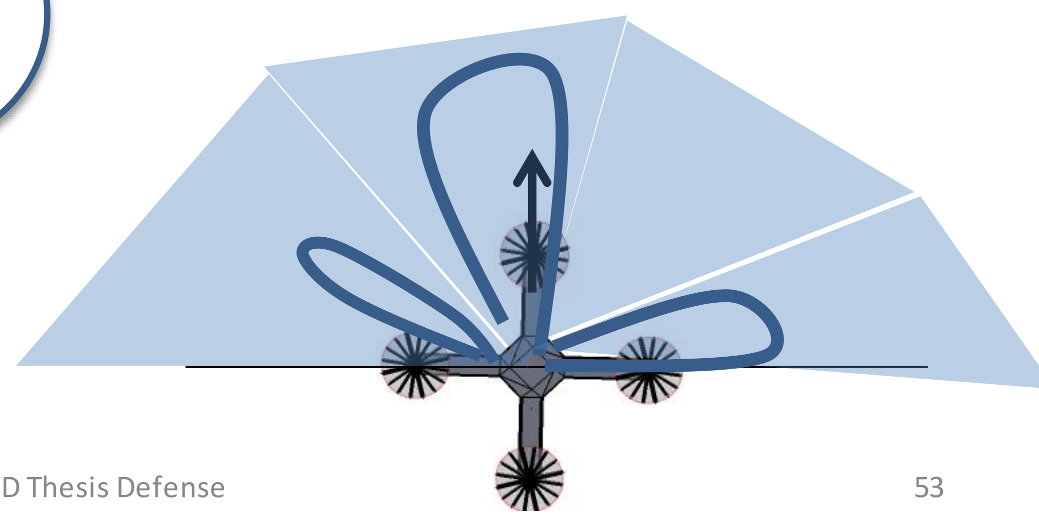
- **What if we had a directional antenna?**

Prediction?

1) C

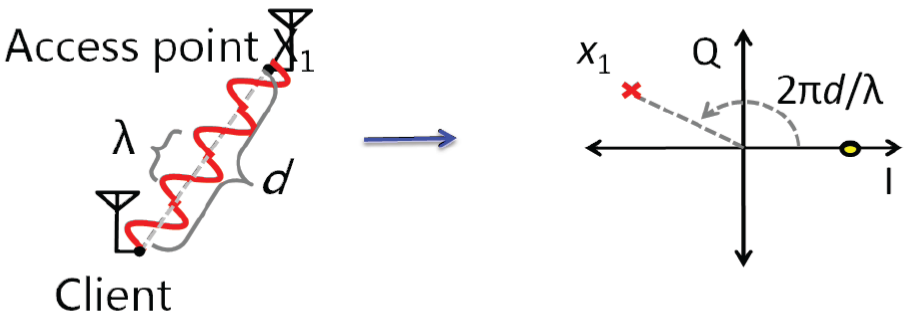
IDEA: Don’t predict.
Find a way to measure directly.

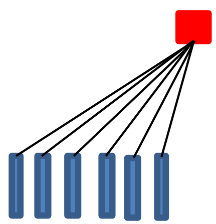
cations



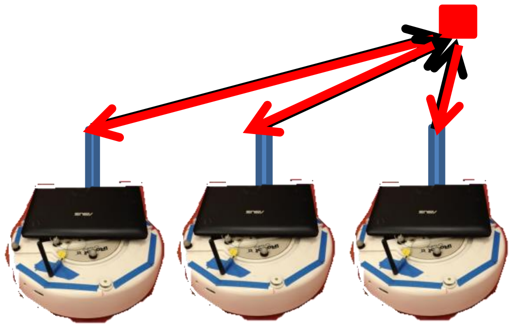
Our Method

Insight: Use *phase* Synthetic Aperture Radar (SAR) [Buckley et. al. '88, Schmidt '86, Fitch '88, Sadler '04 , Jamieson et. al. '13, Katabi et. al. '13]





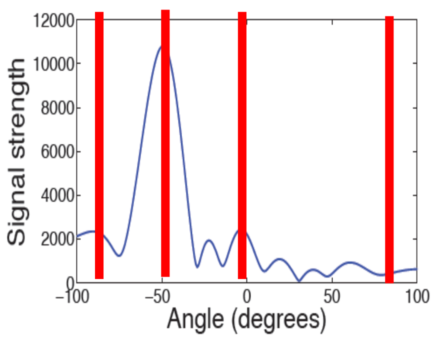
Our method: [Gil, Kumar, Katabi, Rus, *to appear* ISRR '13]



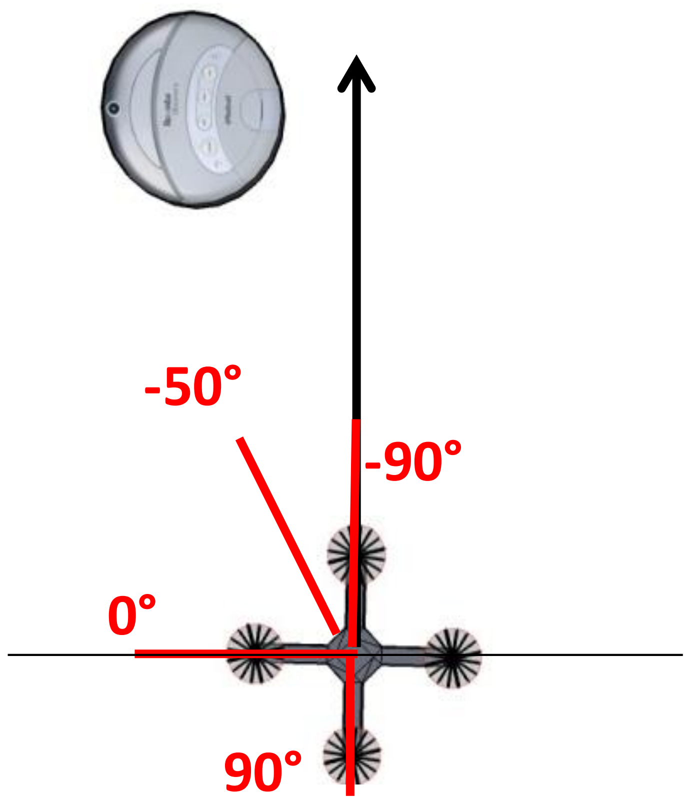
Our Method

Two immediate advantages:

1. Measure directly → Independence of environment
2. Geometric insight → Simple controller



Single Predominant Path (Often LOS)



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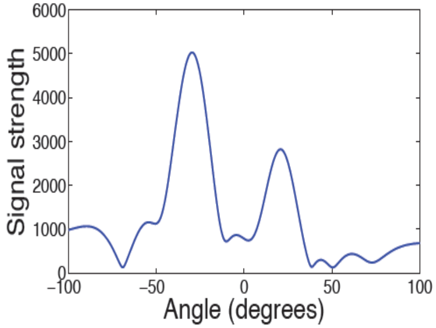
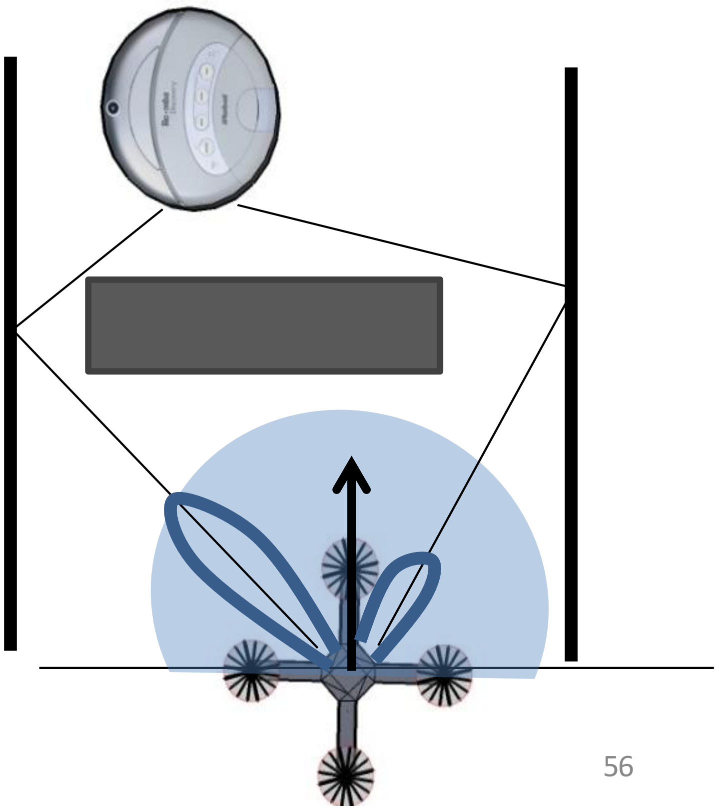
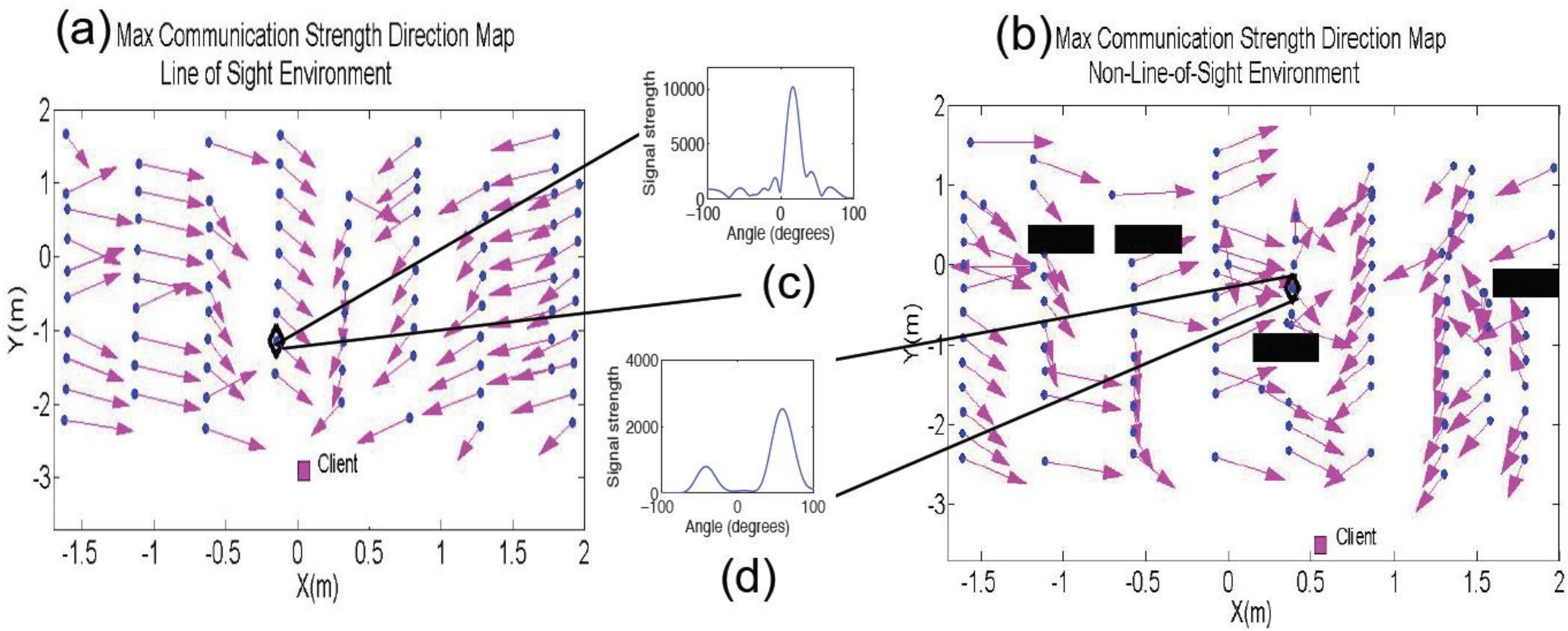


Multipath (Often NLOS)



Measured Channel Feedback



Contributions Outline

I. **Router Placement:** Problem formulation and algorithm for positioning robots

Assumptions

1. ~~Euclidean Disk Model~~
2. ~~Equal demands~~
3. ~~Client position known~~

II. **Large Systems:** Algorithm for efficient computation

III. **Real Communication:** New method for measuring directional information

IV. **Realistic Communication Optimization Problem:** New model that uses channel feedback

Contributions Outline

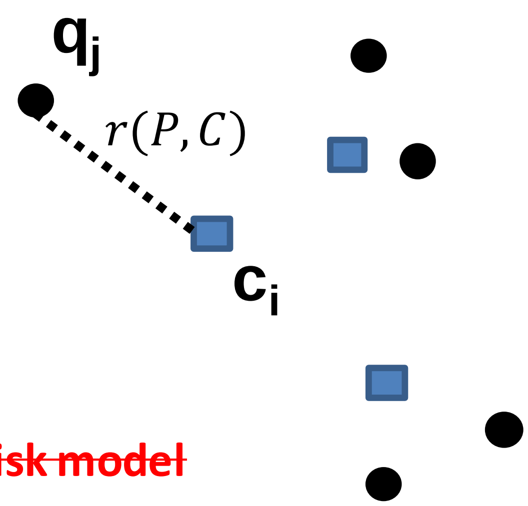
Assumptions
1. ~~Euclidean Disk Model~~
2. ~~Equal demands~~
3. ~~Client position known~~

IV. Realistic Communication Optimization Problem: New model that uses channel feedback

i. Formulation of new optimization problem using real-time feedback
ii. Experimental Validation: satisfy agent demands in actual implementation

Problem Formulation: Realistic Comms

k-center problem: Minimize maximum client distance [Gonzalez ‘85, Vazirani ‘03]



$$C^* = \text{arg}min_C \, r(P, C)$$

$$r(P, C) = \max_{p \in P} \min_{c \in C} \text{dist}(p, c)$$

~~$g_{ij} = dist(p,c) = \sqrt{(p-c)^T(p-c)}$~~ ~~**Euclidean disk model**~~

Legend:
- C: set of robot router positions
- P: set of client agent positions

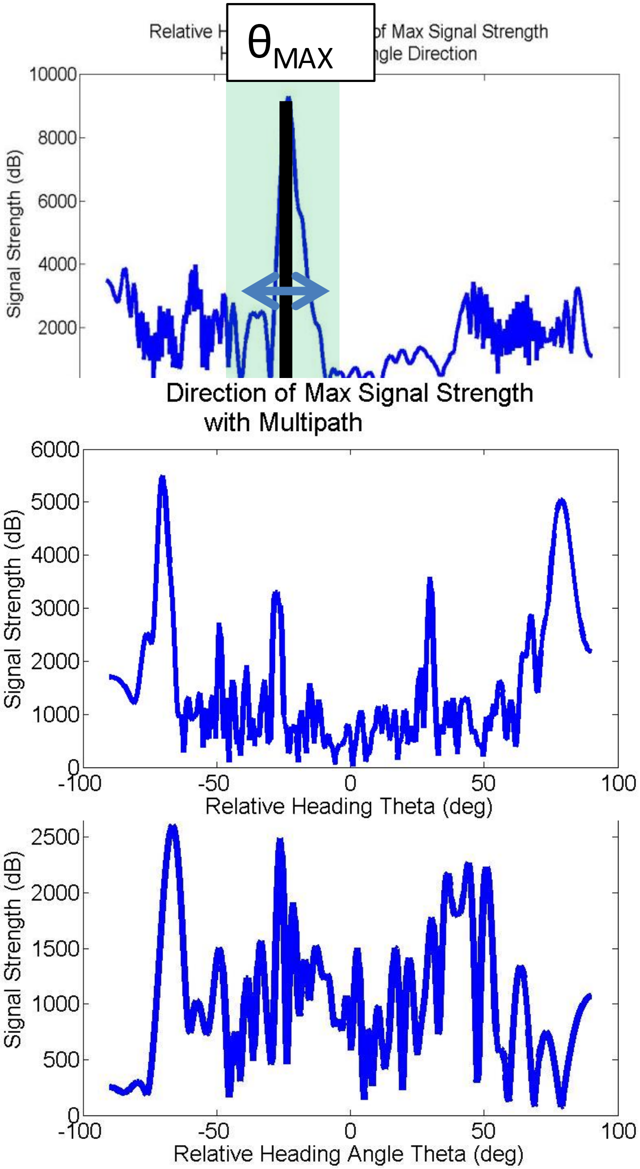
Cost of a edge in the graph :

$$\tilde{g}_{ij} \geq 0$$

Service discrepancy:

$$w_j \geq 0$$

Controller: Encoding Channel Feedback



1) $v_{\theta MAX}$: shortest distance is not straight line path but rather the path along max direction

2) Confidence σ_{ij}: capture "variance" around θ_{MAX} due to noise and/or multipath

High confidence → follow aggressively (larger displacements)

Low confidence → Tradeoff or travel conservatively


Iteration t=53
Sigma around thetaMax=2.056633
Client 1
8%
2%
90 %
8%
8%
84 %

Problem: Communication Model using Channel Feedback

Given: channel feedback for each link (i,j)

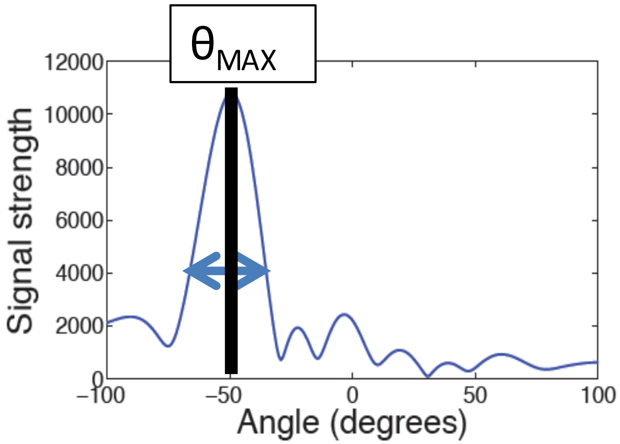
Find: A cost

Current router positions

$$\tilde{g}(c, c_i, q_j, \tilde{q}_{ij}, w_{ij}, p'_{ij}, \theta_{ij}, \sigma_{ij}) \geq 0$$

Optimized router position

Channel feedback



Problem: Communication Model using Channel Feedback

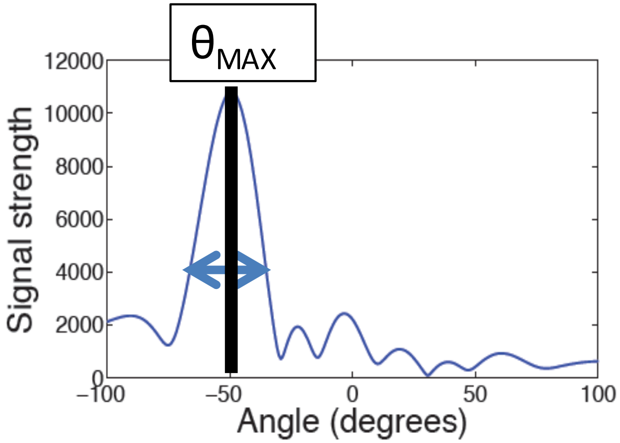
Given: channel feedback for each link (i,j)

Find: A cost

Actual communication quality

$$\tilde{g}(c, c_i, q_j, \tilde{q}_{ij}, w_{ij}, p'_{ij}, \theta_{ij}, \sigma_{ij}) \geq 0$$

Communication demands

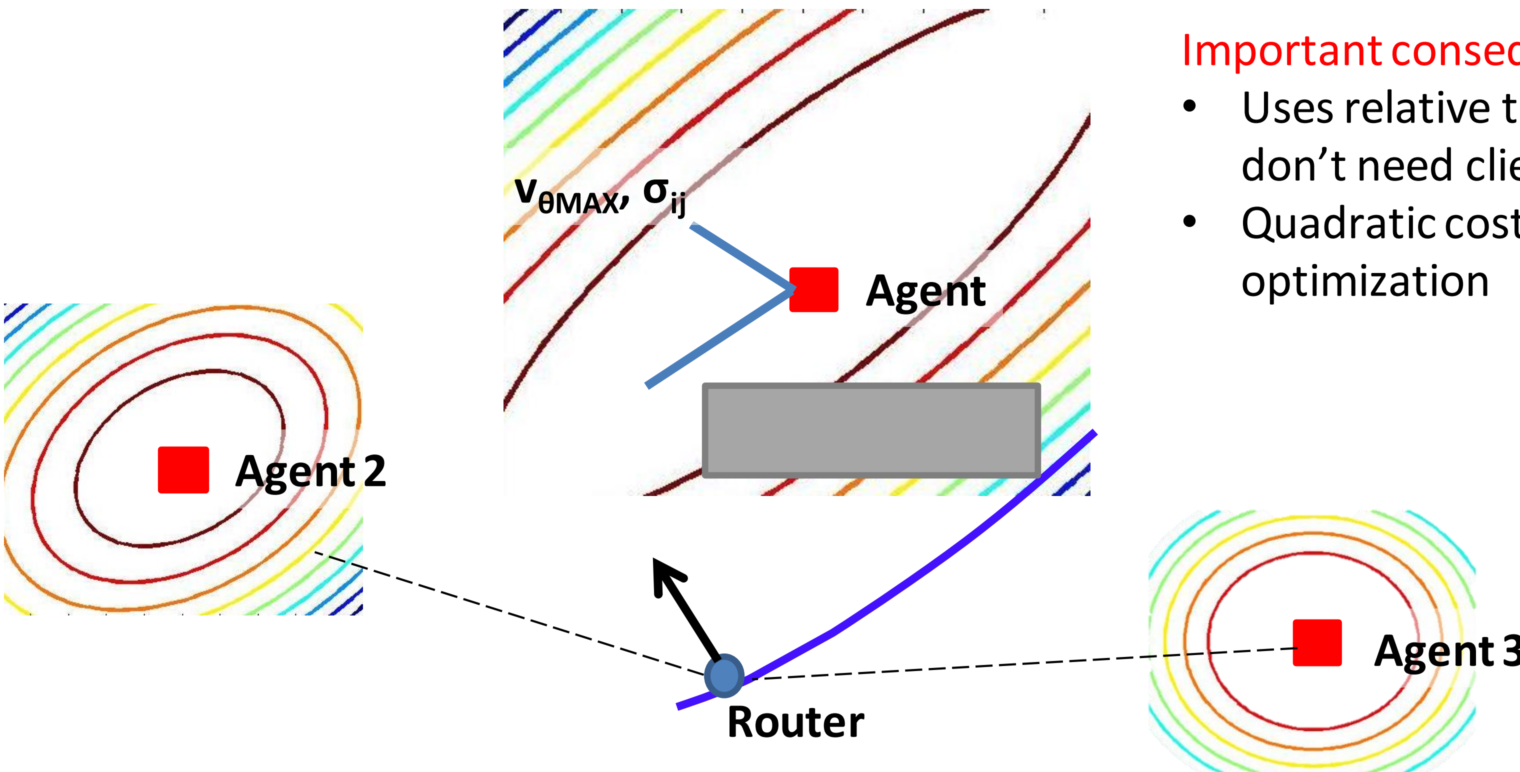


$$w_j = \max\left\{\max_{i\in\{1,\ldots,k\}} \frac{q_j - \tilde{q}_{ij}}{q_j}, 0\right\}$$ Service discrepancy

such that the minimization of $\tilde{g}$ wrt c_i for all $1 \leq i \leq k$ results in a configuration of routers C that minimizes service discrepancies w_j for all clients $1 \leq j \leq n$

Controller: Encoding Channel Feedback

Intuition: Use channel feedback to "skew" space → use generalized distance metric [Gil, Kumar, Katabi, Rus, *to appear* ISRR '13]



Important consequence:

- Uses relative to heading → don't need client positions
- Quadratic costs → easy optimization

Scaled gradient descent [*Nonlinear Optimization* Bertsekas, 1997]

Contributions Outline

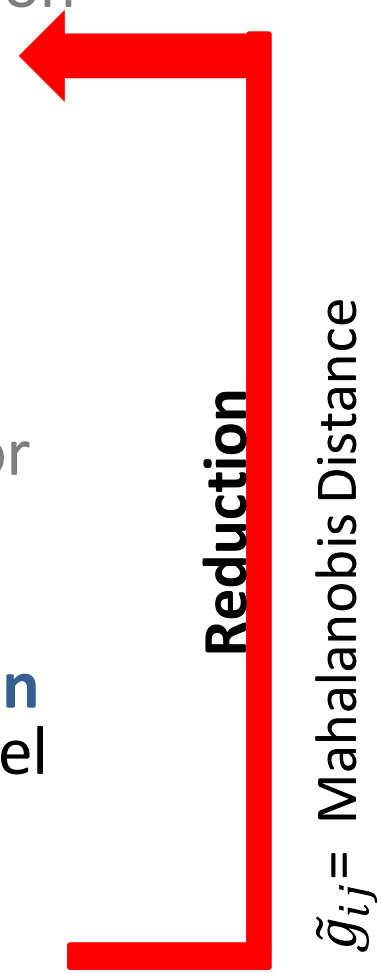
I. **Router Placement:** Problem formulation and algorithm for positioning routers

II. **Large Systems:** Algorithm for efficient computation

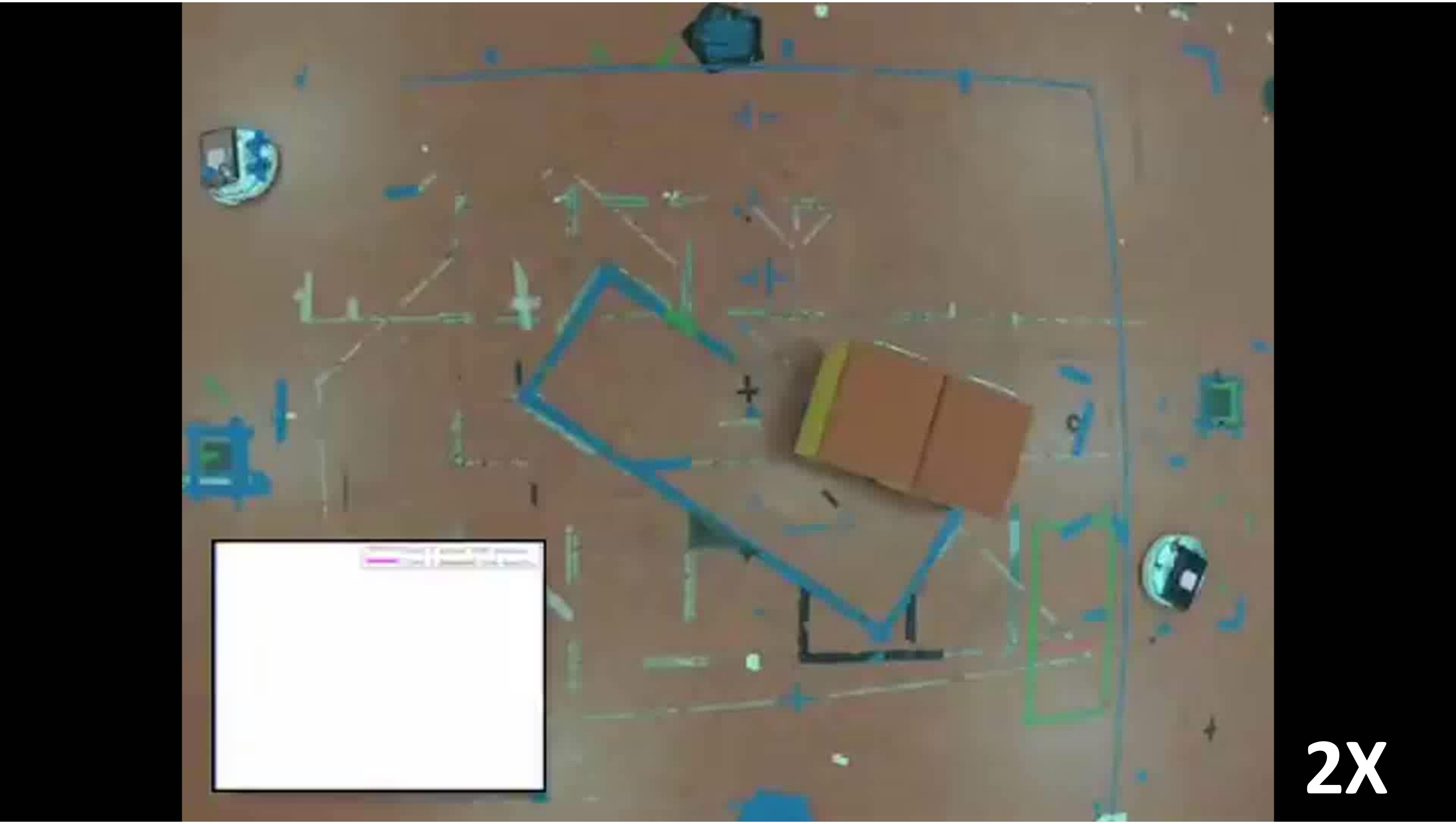
III. **Real Communication:** New method for measuring directional information

IV. **Realistic Communication Optimization Problem:** New model that uses channel feedback

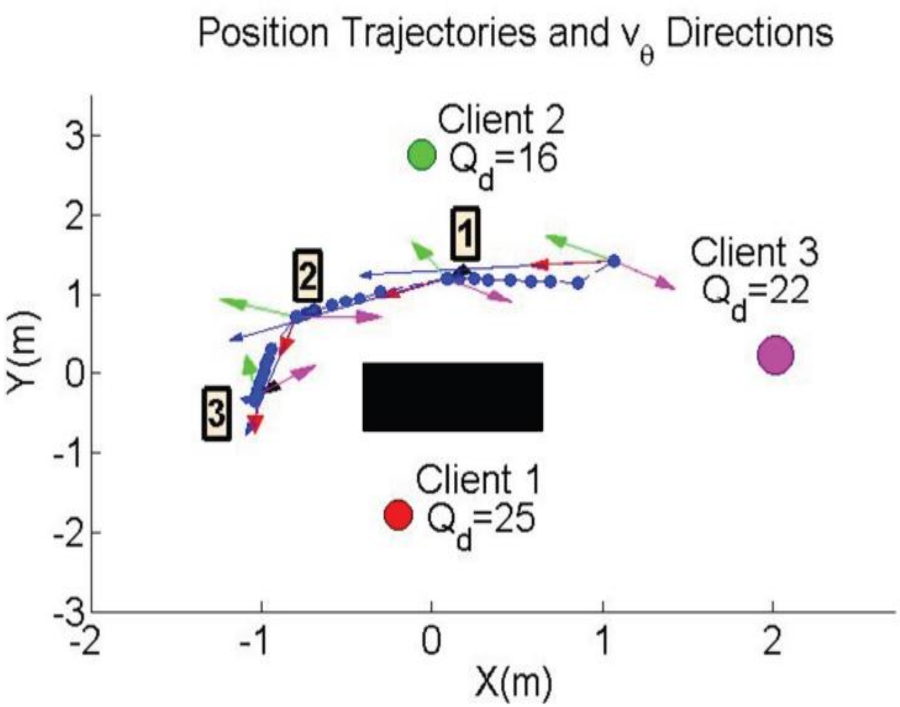
– Satisfy agent demands in actual implementations



Using Real-time Channel Feedback

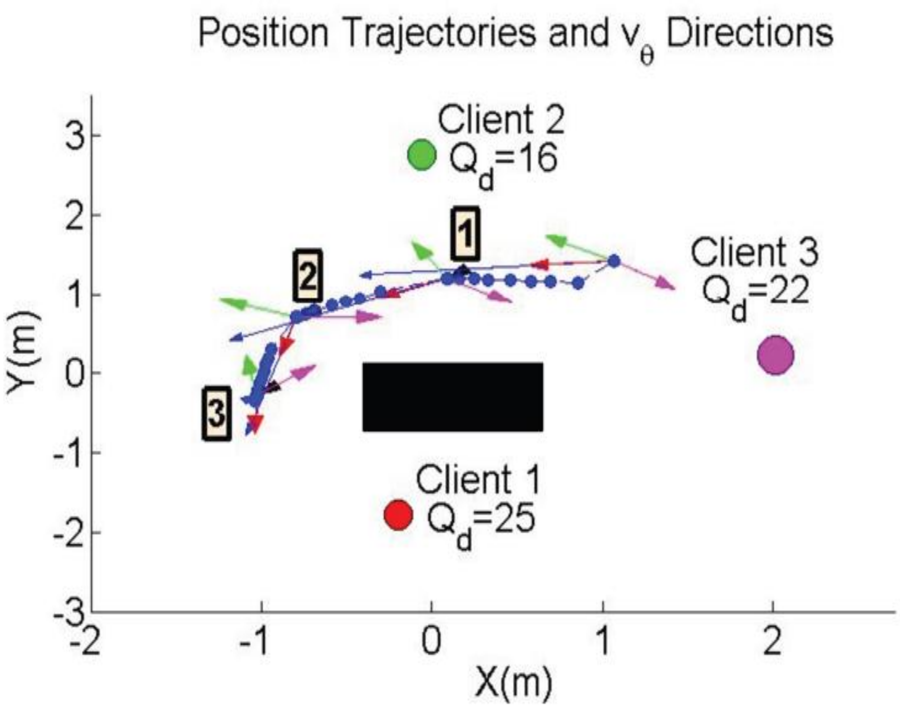


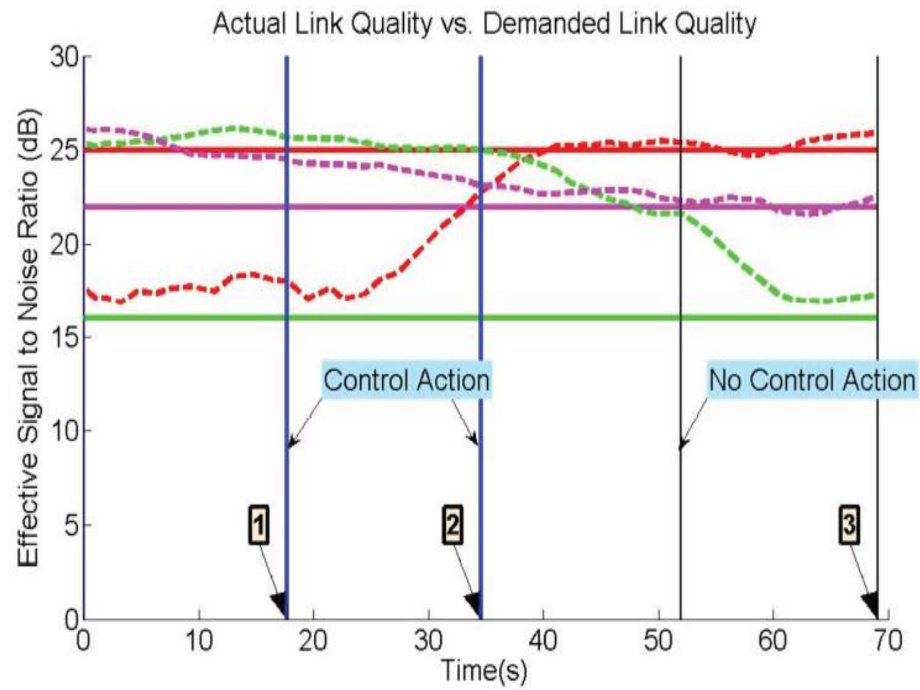
Multiple Client Agents



- Multiple clients with service tradeoffs

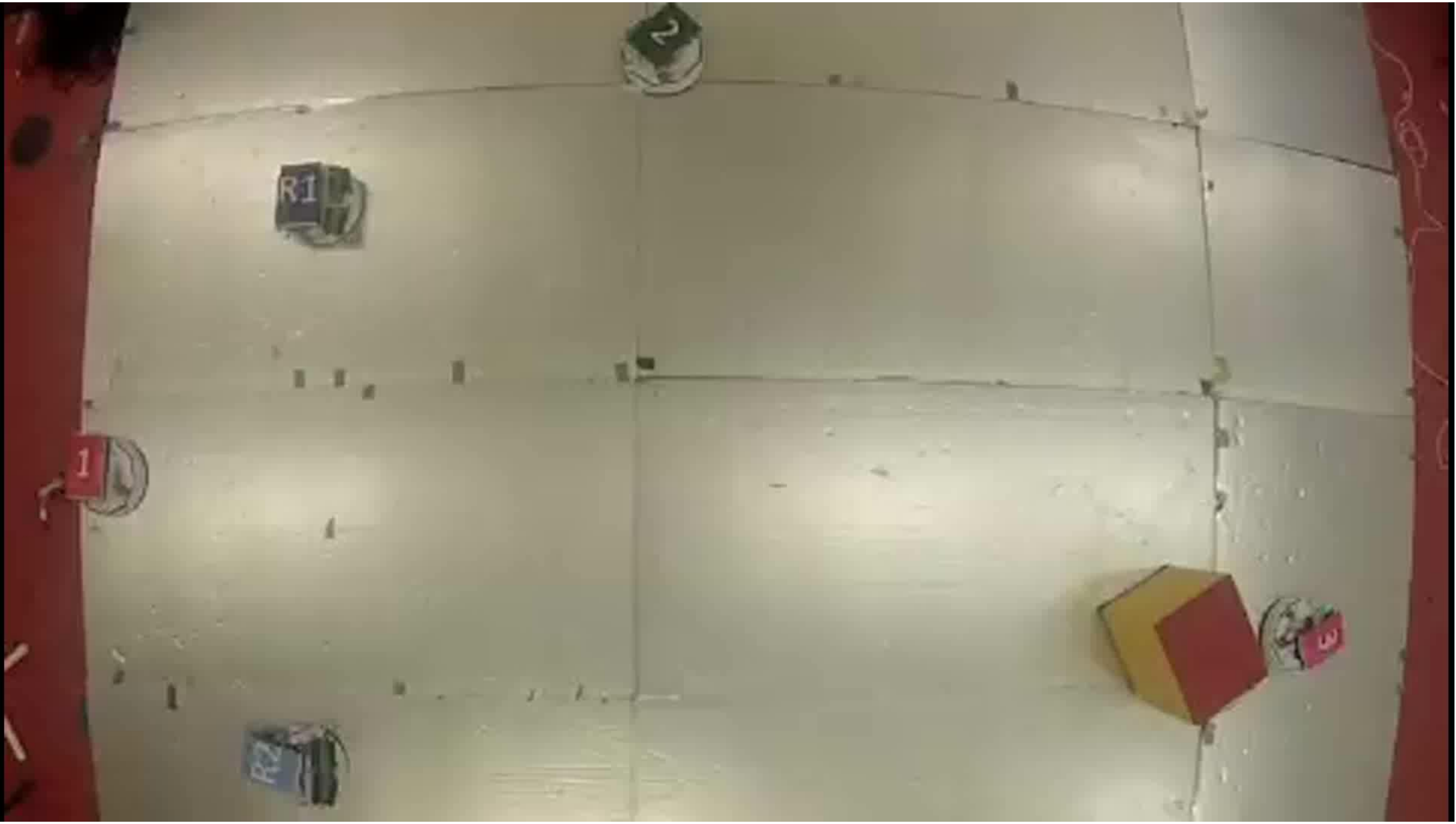
Multiple Client Agents



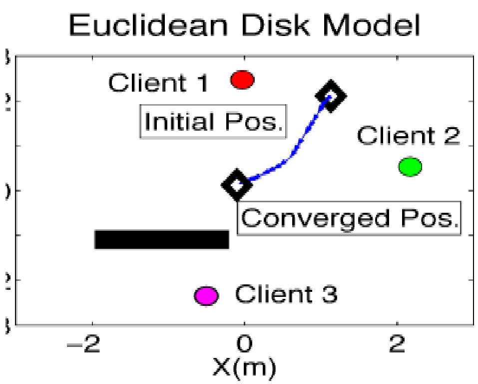


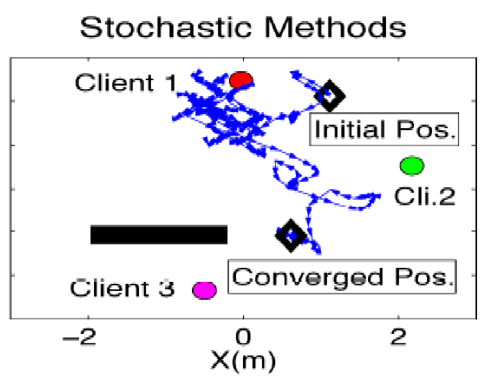
- Multiple clients with service tradeoffs

Multi-Veh Network: Agent Tradeoff

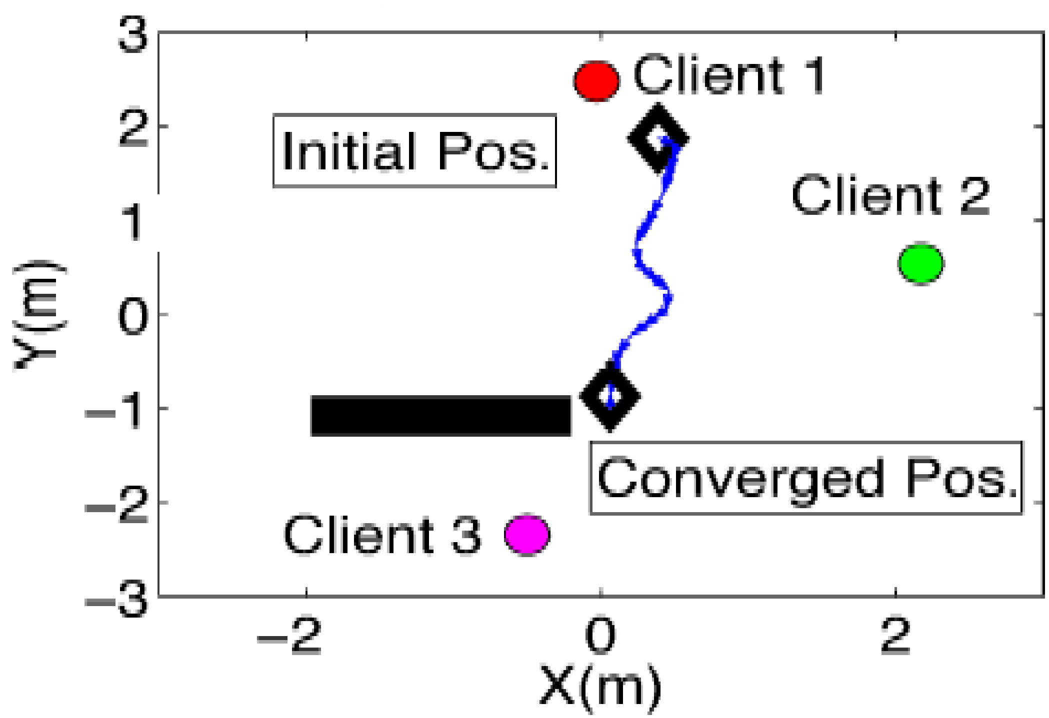


Comparison to Other Methods





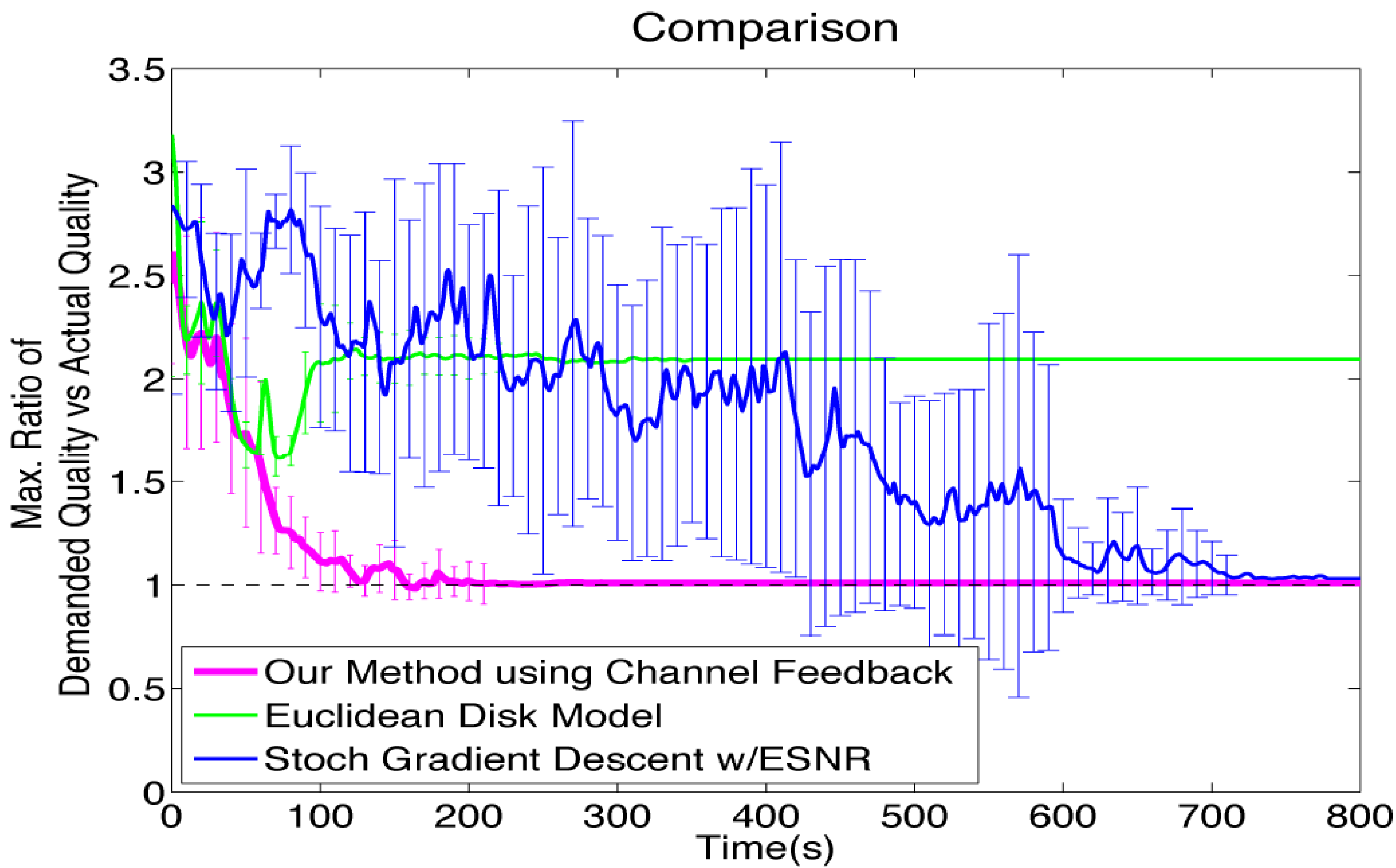
Previous methods



Our method:

- demonstrates efficient convergence
- solution satisfies all client agent demands

Comparison to Other Methods



Thesis Contributions in a Nutshell

Realistic Communication Coverage

- Optimal Comm Coverage for Large Mobile Teams
- Locally Optimal (Distributed) Comm Coverage

Problem Formulation: Optimize over dynamics and connectivity

- Router Placement (Algorithmic)
- Globally optimal allocations for small problem sizes (Theoretical)
- Human/robot with real-time repositioning (Experiments)
- Error bound as number of clients increases (Theoretical)
- Large networks (Experiments)

Problem Formulation: Physical model interference

- Lyapunov stability to local minima (Theoretical)
- Connectivity maintenance (Theoretical)
- Robustness to failure (Experiments)
- Comms with infeasible regions (Algorithmic)
- GPS-denied indoor env. (Experiments)

Channel Feedback: Signal quality directional profile

- Wireless Channel Mapping (Experiments)

Realistic Comms Optimization

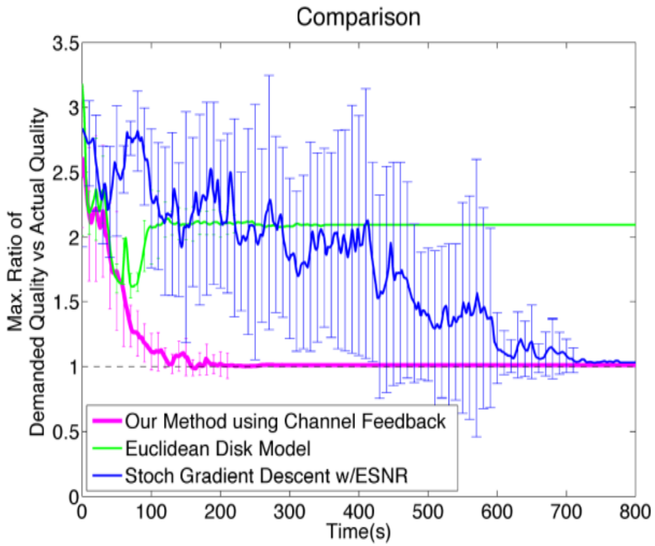
- Satisfy real-time client demands (Experiments)
- Comparison to other methods (Experiments)

Legend:
- Theoretical
- Algorithmic
- Experiments

Conclusion

Solve the communication coverage problem by controlling the position of robot routers in real-world environments

- **Algorithms** for scalable solution
- **New methods** for realistic communication model (not Euclidean Disk)
- **New optimization formulation** that is simple yet use channel feedback
- **Real results** in unknown environments



Acknowledgements I