Trade-offs Between Mobility and Density for Coverage in Wireless Sensor Networks

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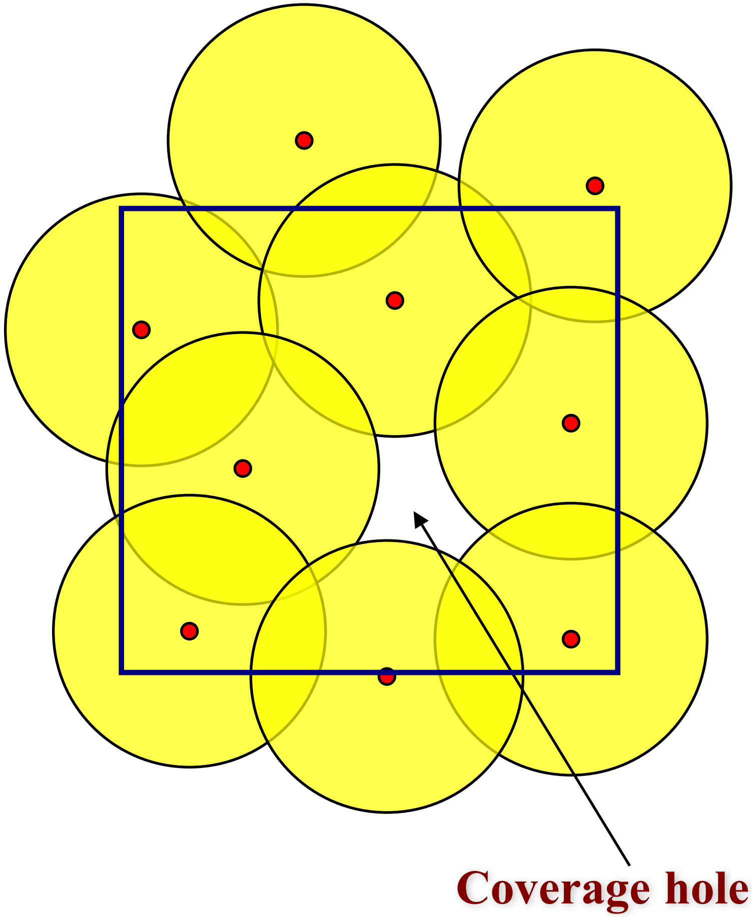
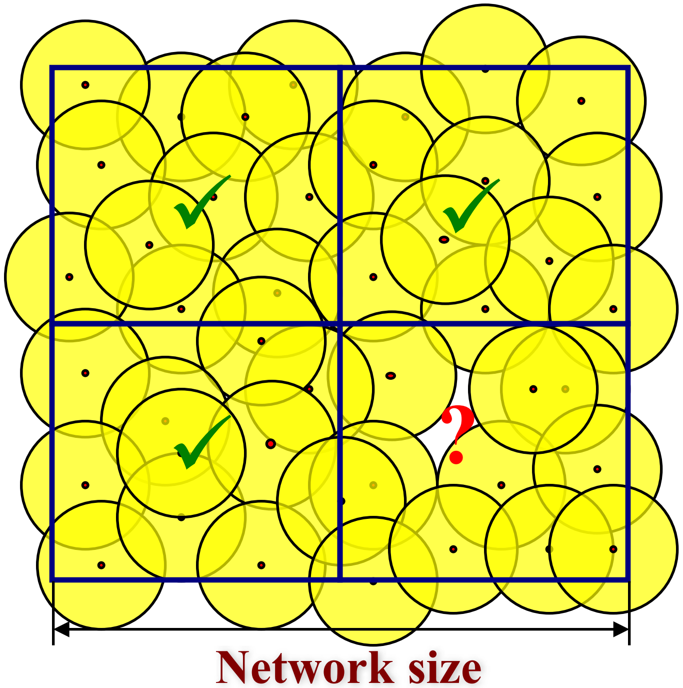
Coverage in sensor networks

- Sensors are often randomly scattered in the field
- Sensing region can be abstracted as a disk around sensors
- *k*-coverage requires each point to be covered by at least *k* sensors
- Areas not covered by sensing disks are called coverage holes



Density requirements in static network



- Larger network has higher probabilities to have coverage holes
- Increase sensor density can reduce the coverage holes
- To ensure the network is fully *k*-covered with high probability, the sensor density needs to increase as [Zhang et al. 2004]

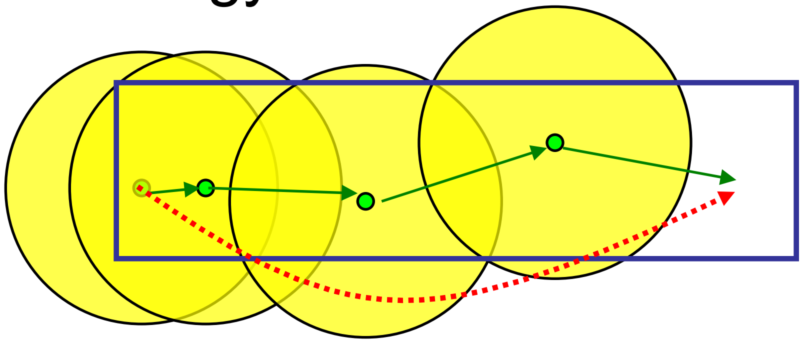
$$O(\log L + k \log \log L)$$

Over-provisioning factor

- **Defined as** $= \quad / k$
- **Shows how efficient the coverage scheme is**
- **Deterministic sensor networks have *constant* over-provisioning factors**
- **In random static sensor networks, the over-provisioning factor increases with network size, so it is *inefficient*.**

Network of mobiles

- **Mobiles can relocate them selves to heal holes**
- **Movement consumes much more energy than sensing and communication**
- **How to move efficiently?**
  - -- Cascaded movement [Wang et al. 2005]
  - -- Each mobile moves only over a short distance
  - -- Save both energy and time



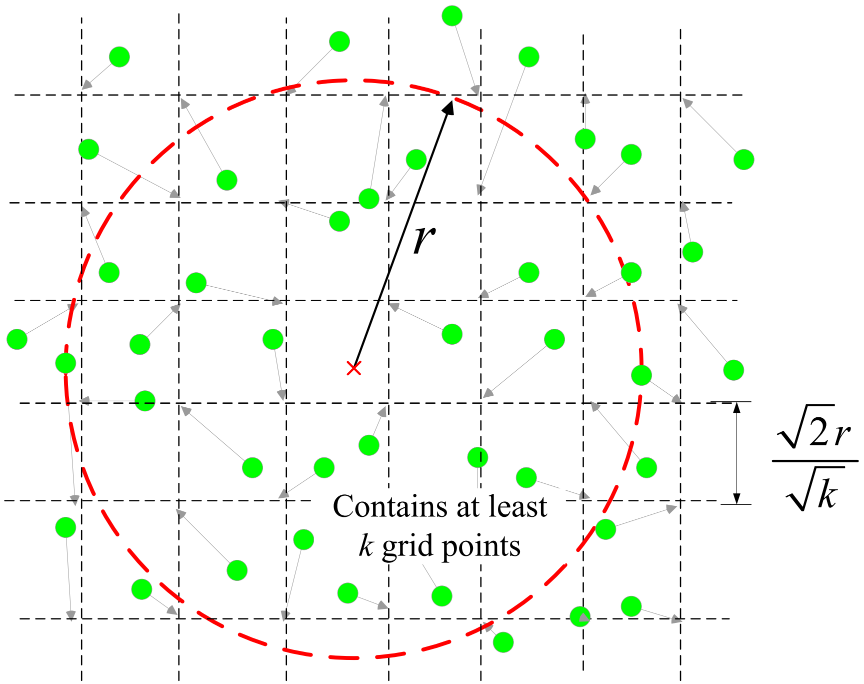
What's the maximum movement distance ?

Networks of mobiles

- All sensors can move, initially uniformly distributed
- The network is divided to grids of side length $\sqrt{2}r/\sqrt{k}$
- Mobiles have sensing radius of *r*
- Match mobiles to grid points – Minimax matching problem
- Each mobile only needs to move for a distance of

$$O(1/\sqrt{k}\,\log^{3/4} L)$$

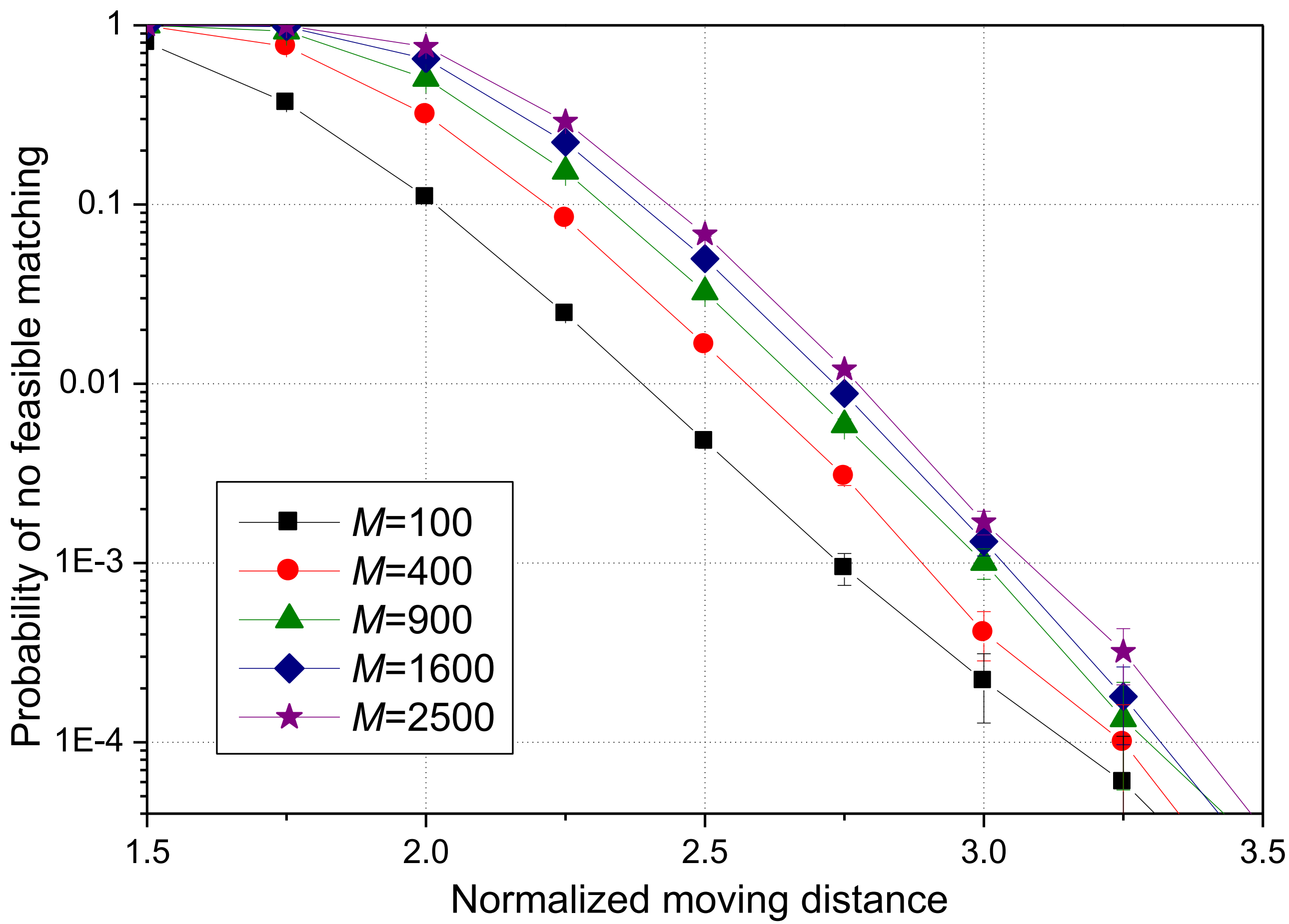
- The network can be *k*-covered with a constant over-provisioning factor



Mobile coverage

- Each mobile only needs to move once over a limited distance
- Only limited energy is used in mobility, mobile can be cheap and simple
- The scaling factor in density is converted to moving distance
- Mobiles need to coordinate with each other to provide full coverage

Simulation results



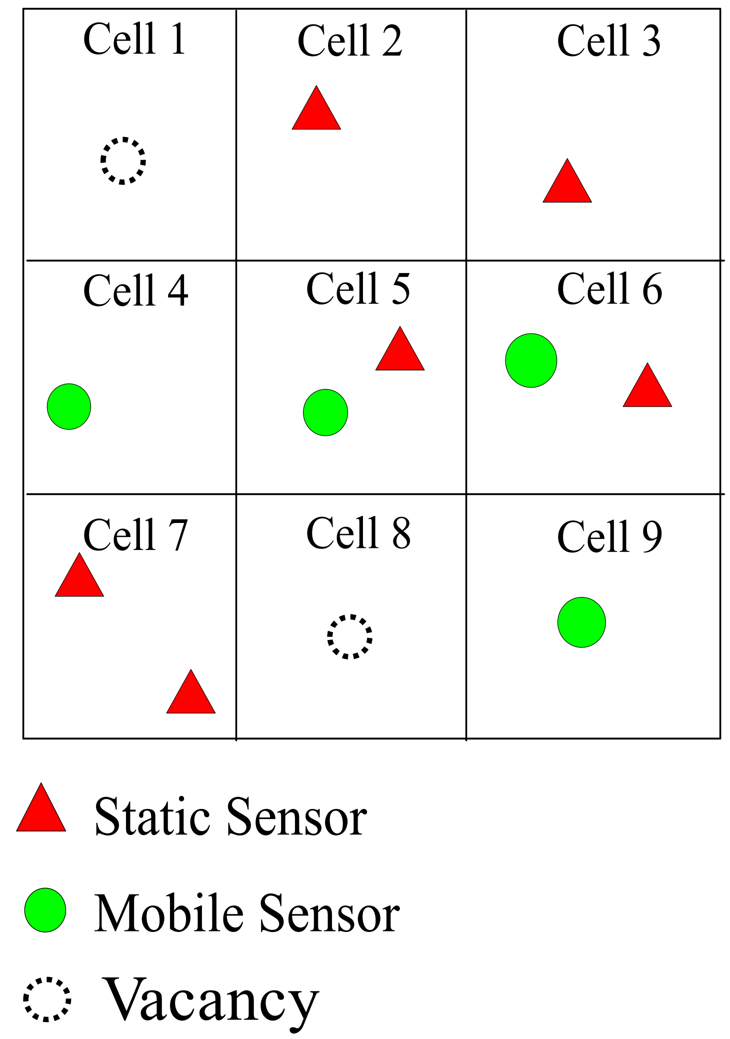
- **Demo Available at http://cnds.ece.nus.edu.sg/mobile/mobile.html**
- **For a 10*10 network, sensors need to move over at most 2 grids to achieve more than 90% success rate.**

Heterogeneous networks

- **Mobiles are more expensive than static sensors**
- **How to reduce the network cost?**
  -- Not all sensors need to move
- **Heterogeneous network**
  -- only use a limited number of mobiles
  -- scatter mobiles randomly with static sensors
- **Constructively show the network performance lower bound**

Network structure

- Divide network to cells
- Static sensor density: *k* sensors per cell
- Mobile density: $\frac{\sqrt{k}}{\sqrt{2}}$ mobiles per cell
- Cell may contain vacancies due to random deployment
- Matching mobile sensors to vacancies
- Vacancy distribution is not uniform



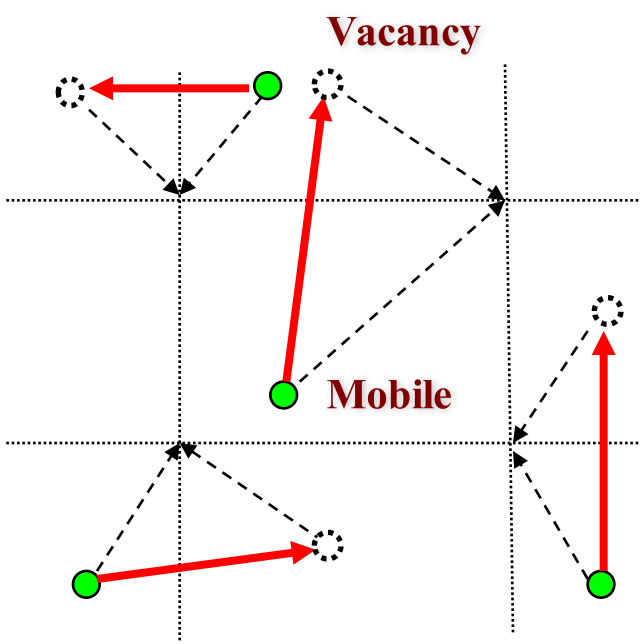
Matching between vacancies and mobiles

Two step matching

1. Match mobiles to a regular grid, maximum matching distance $O(\log^{3/4} L)$

2. Match vacancies to the same grid $O(\log^{3/4} L)$

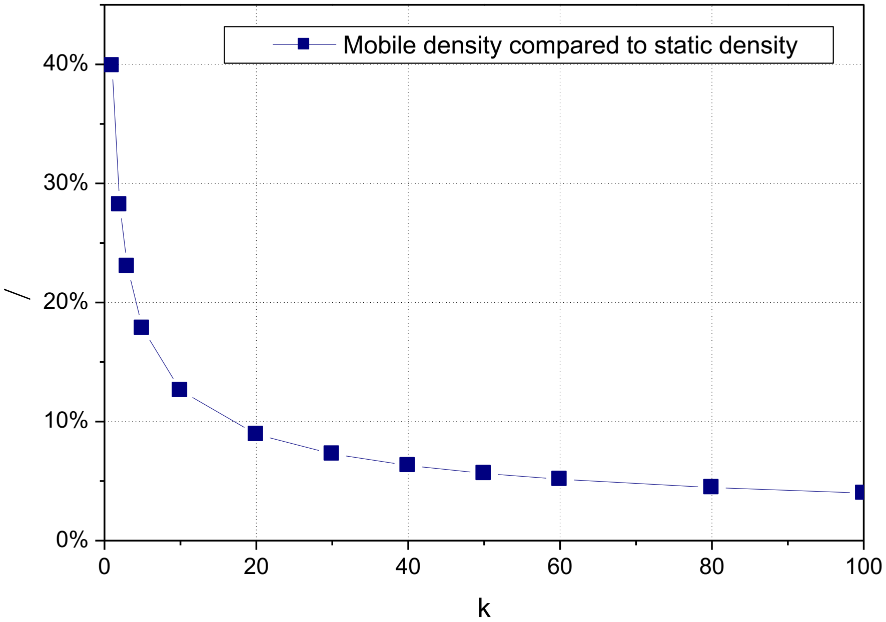
Overall maximum moving distance $O(\log^{3/4} L)$



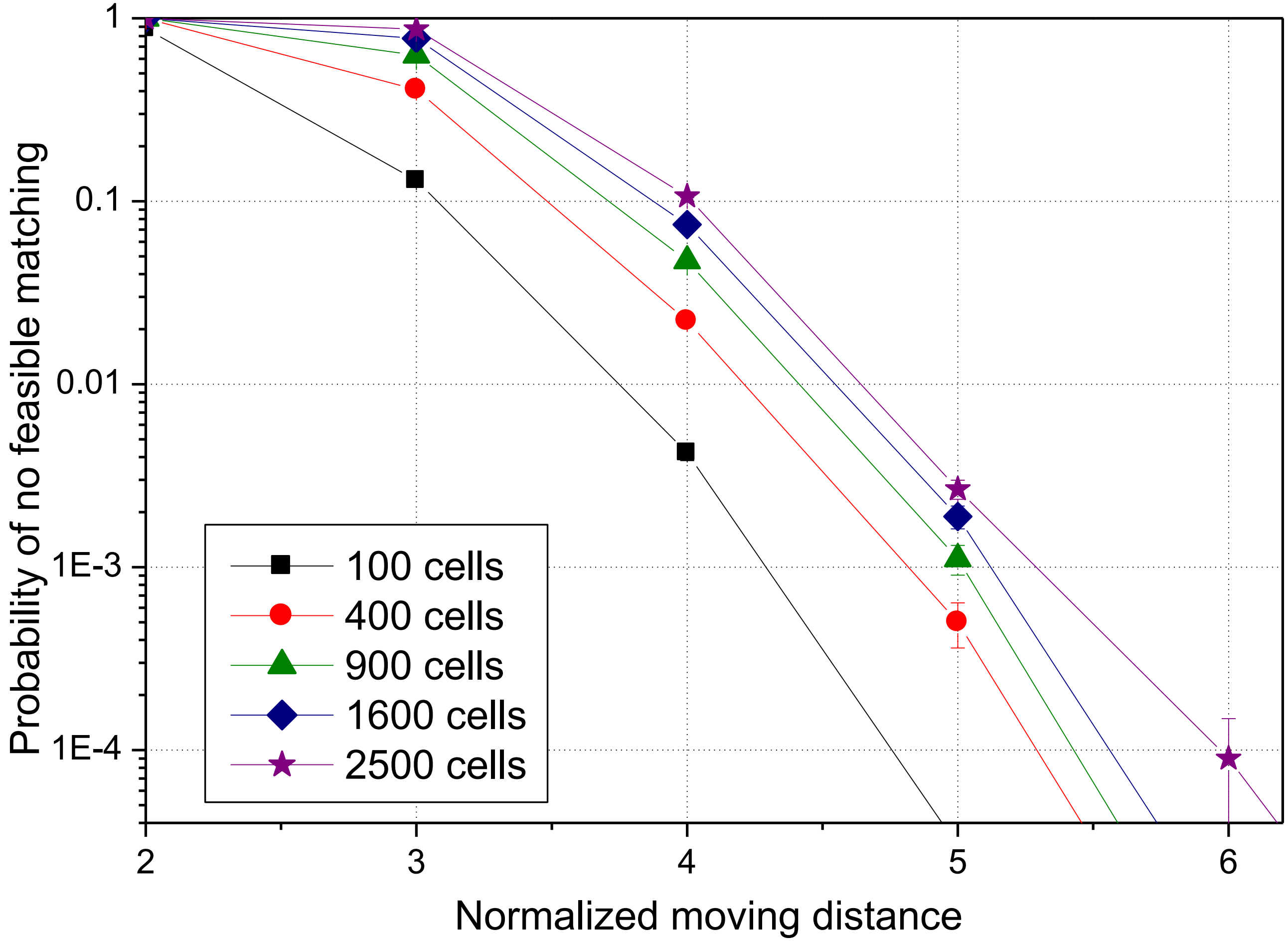
Heterogeneous networks

Results summery

- Only a small fraction of $O(1/\sqrt{k})$ sensors need to be mobile
- The overall over-provisioning factor is constant
- Maximal mobile movement distance is $O(\log^{3/4} L)$



Simulation



1
0.1
0.01
1E-3
1E-4
Probability of no feasible matching
2
3
4
5
6
Normalized moving distance
100 cells
400 cells
900 cells
1600 cells
2500 cells

Mobility algorithm

- The matching problem can be treated as a network flow problem

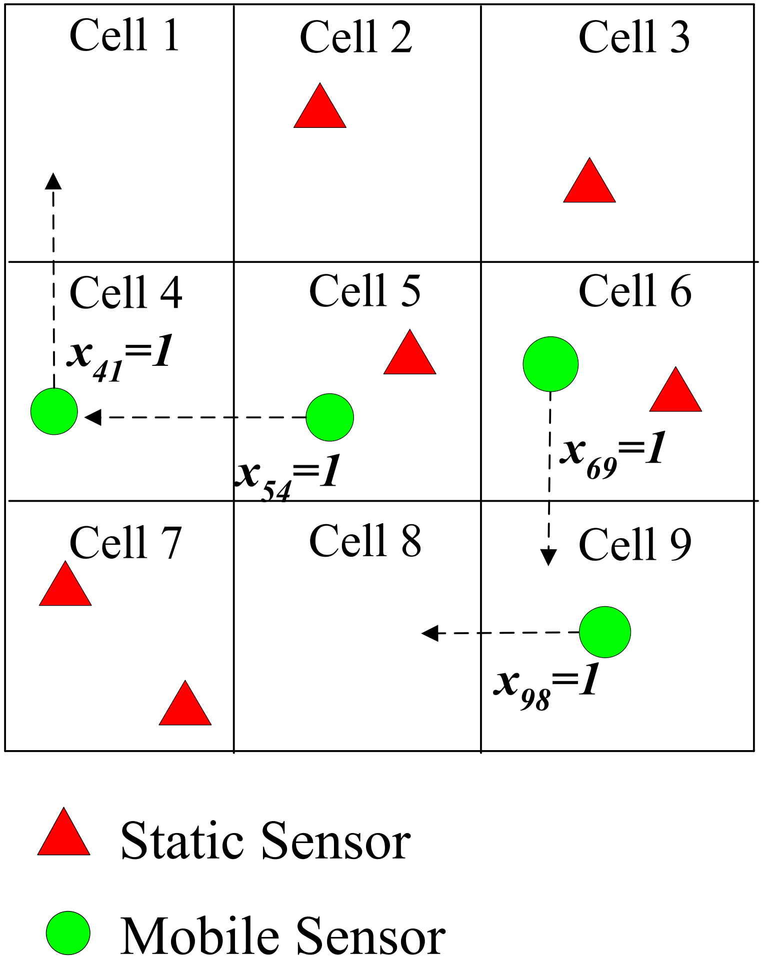
$$\textit{Minimize} \quad \underset{i,j}{} \; c_{ij} \cdot x_{ij}$$

$$s.t. \quad \underset{j}{} \; x_{ji} \quad \underset{j}{} \; x_{ij} \quad v_i \quad m_i \qquad i$$

$$\underset{j}{} \; x_{ij} \quad m_i \qquad i$$

$$x_{ij} \quad 0 \qquad i, j$$

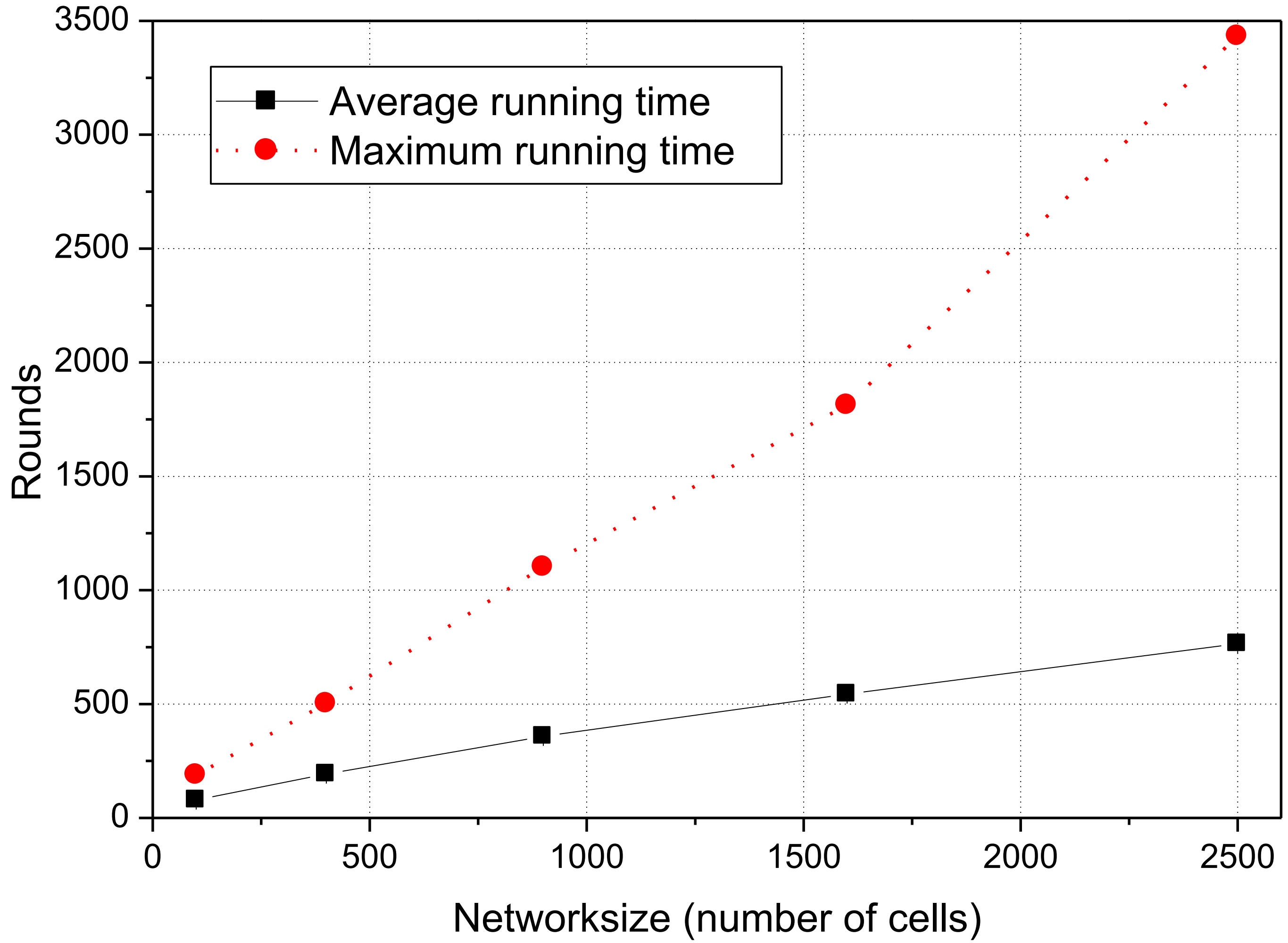
- Totally Unimodular → x_{ij} are integers
- Solve this problem through the distributed push-relabel algorithm



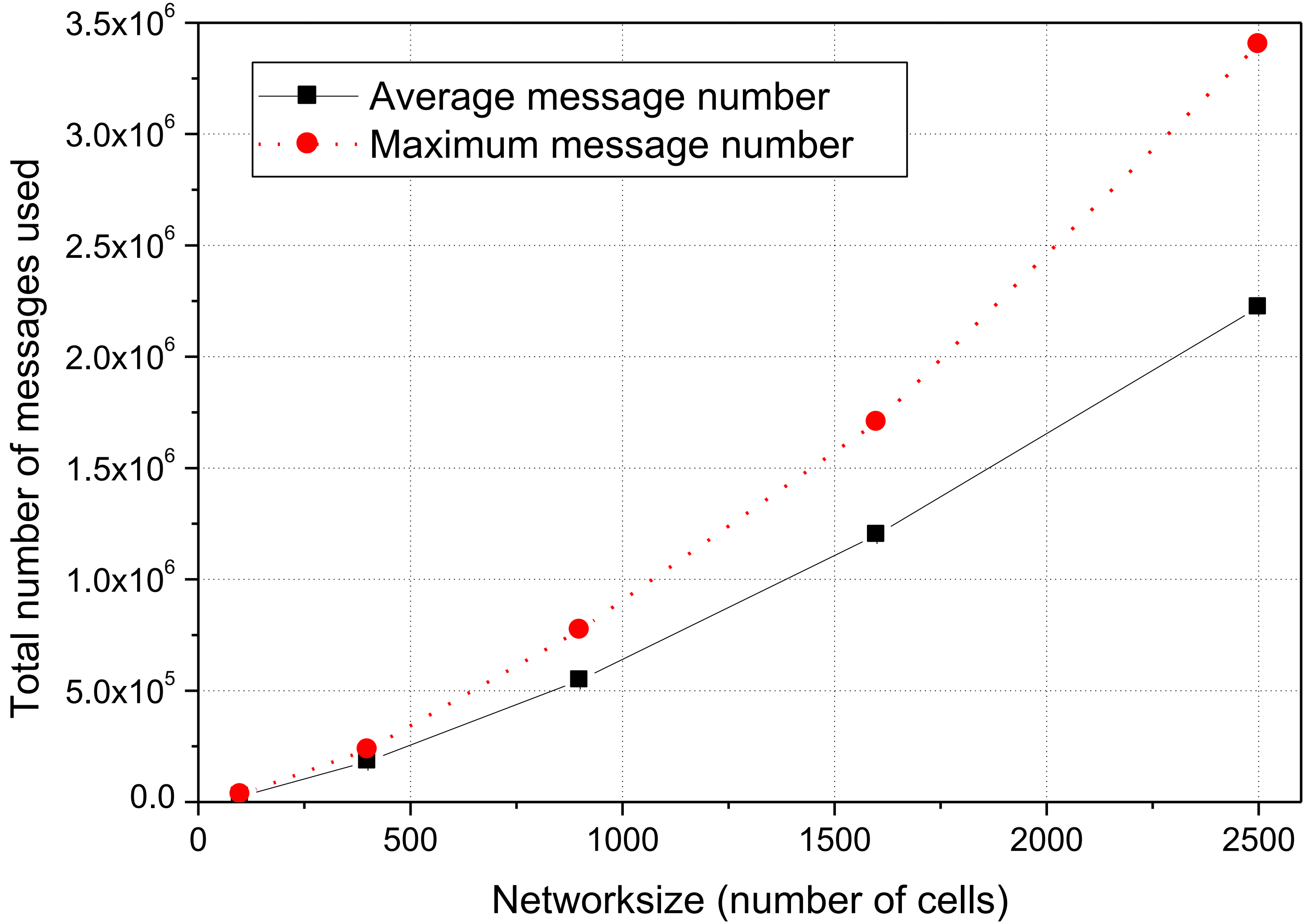
Push relabel algorithm

- Solve the maximum flow problem with push-relabel algorithm
- Executed in delegates of cells
- Cell can push their vacancies to neighboring cells which has lower height than it
- Cells only need to maintain information about itself and height of its neighbors
- Complexity $O(L^2)$
- Number of message exchange $O(L^3 \log^{3/2} L)$

Experimental running time

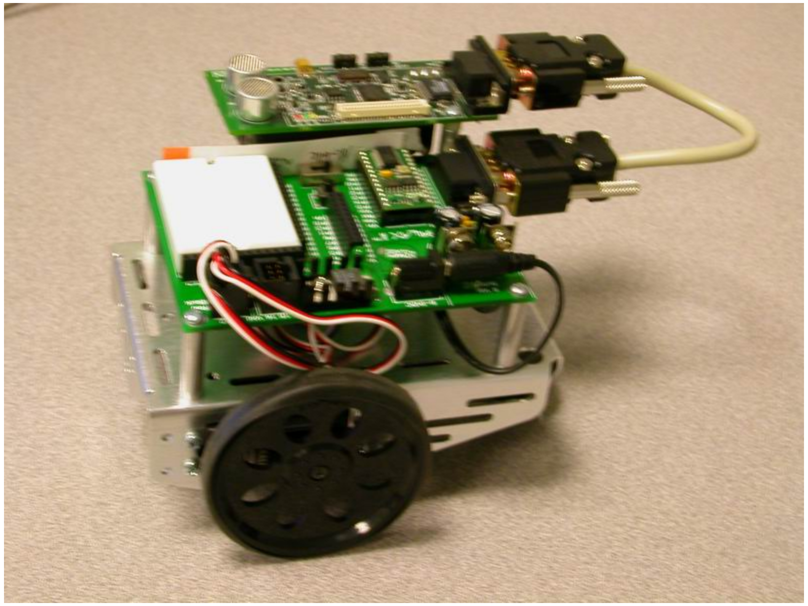


Experimental message usage

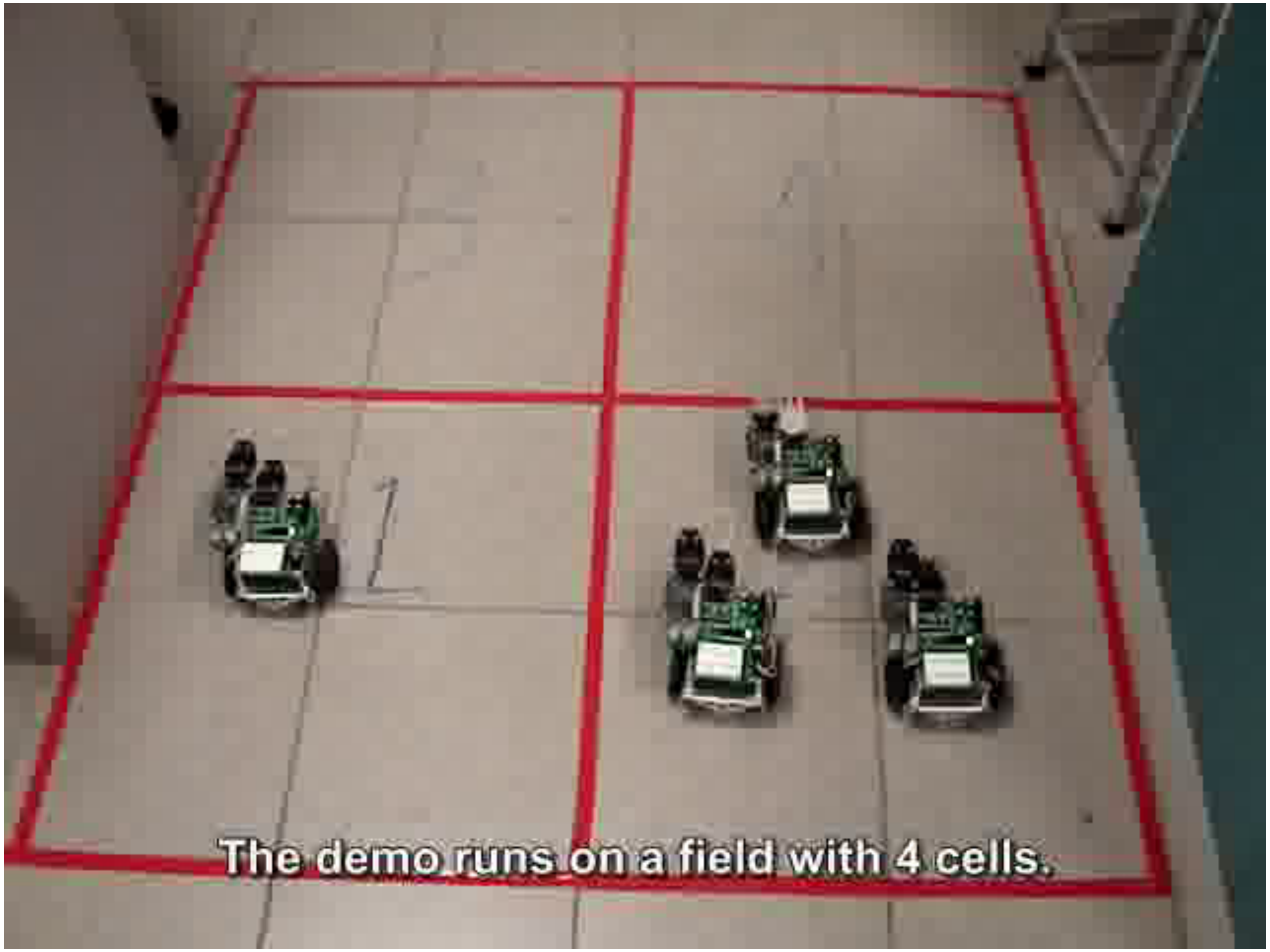


Mobile sensor implementation

- Boe Bot robot + Cricket Motes
- Based on the distributed push-relabel algorithm
- Light-weighted, 10K bytes programming space + 300 bytes RAM
- Robust to message loss



Demo Video



Available at http://cnds.ece.nus.edu.sg/mobile/mobile4.mpg

Conclusion

- **Limited mobility can greatly improve the network coverage**
- **The movement schedule can be solved in a distributed way**
- **Future works**
  -- continuous network coverage
  -- use mobility to improve network reliability

Thank you!

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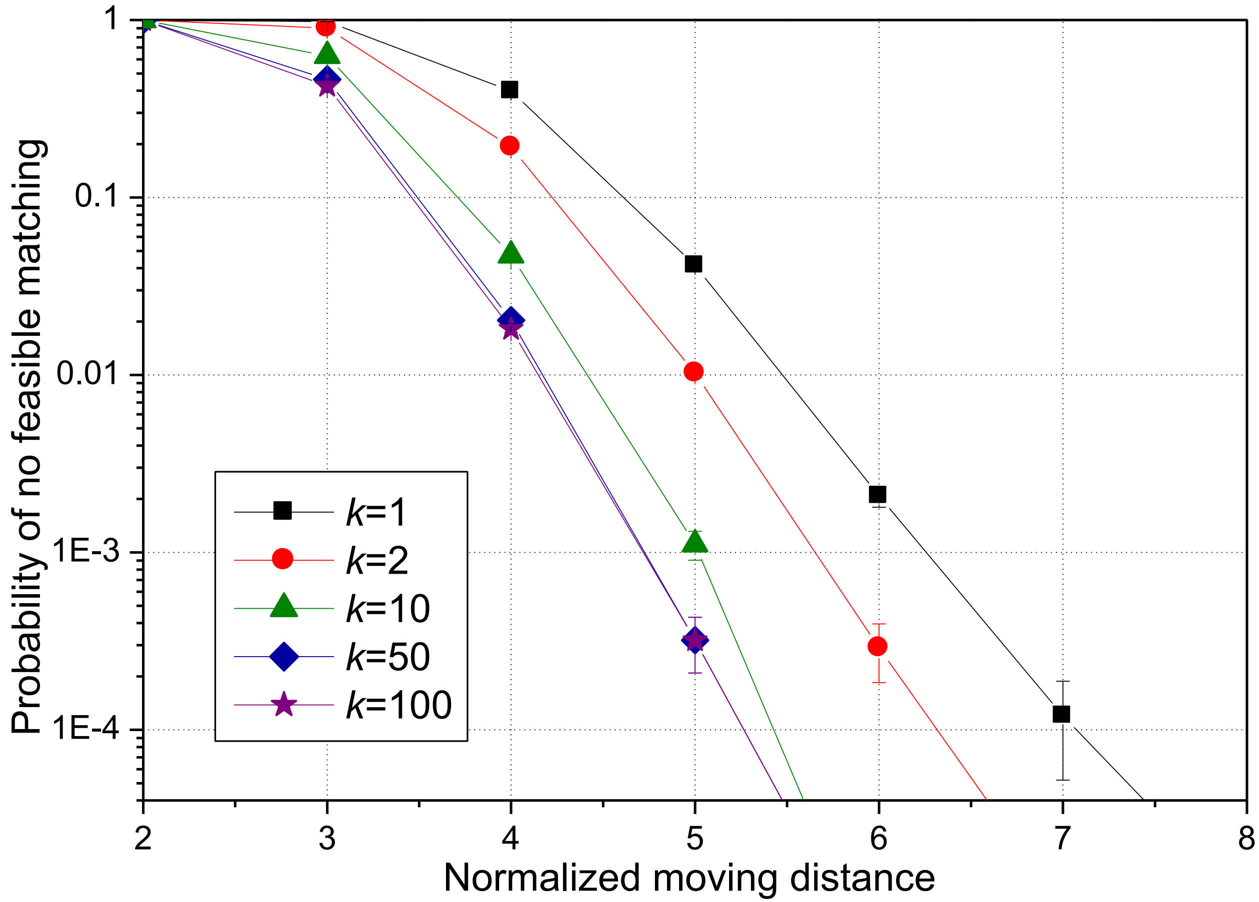
Outline

- Introduction
- Coverage in network with all mobiles
- Heterogeneous sensor network
- Distributed mobility algorithm
- Conclusion

Simulation (different k)



Minimax matching

- The coverage problem can be converted to a matching problem
- Each randomly deployed mobile needs to be matched to a grid point
- We can directly use the minimax matching results on uniformly distributed points to lattice points to get the movement distance bound