Coverage by Directional Sensors

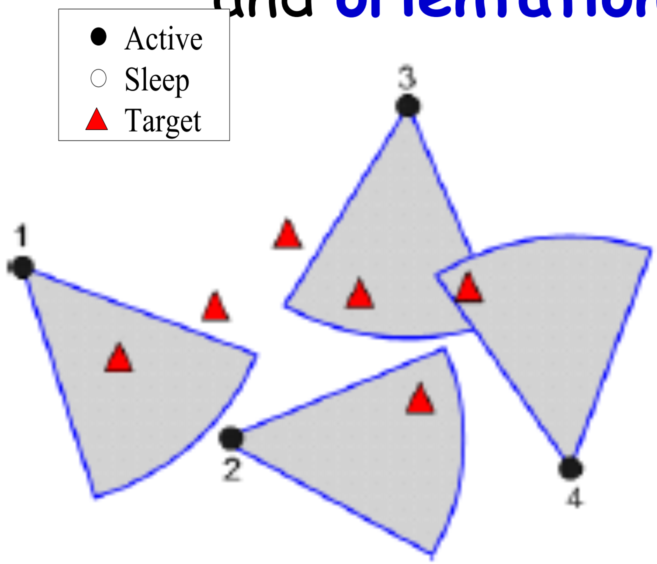
Jing Ai and Alhussein A. Abouzeid
Dept. of Electrical, Computer and Systems Engineering
Rensselaer Polytechnic Institute
Troy, NY 12180, USA
aij@rpi.edu,abouzeid@ecse.rpi.edu
http://www.ecse.rpi.edu/Homepages/abouzeid/R&P.html

WiOpt 2006

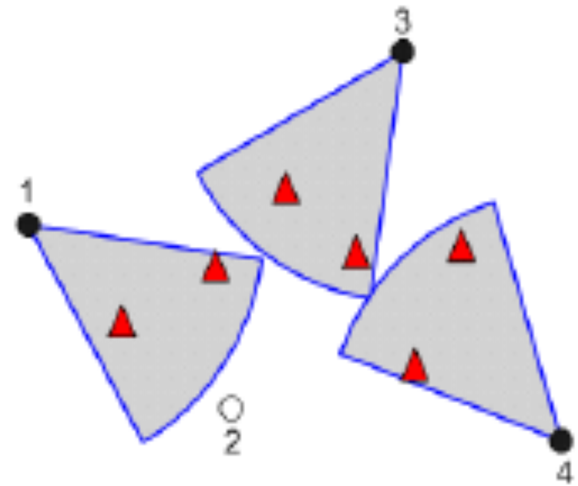
Boston, April 6th, 2006

Motivation

- What's new in coverage by directional sensors?
  - In a setting target coverage as shown below, we can see that whether a target is covered or not determined by both sensor's **location** and **orientation**.



Random deployment



After reconfiguration

Problem Assumptions

- Assume directional sensors can acquire (location) knowledge on targets within maximum sensing ranges.
- Assume directional sensors can only take a finite set of orientations without sensing region overlapped.
- Target-In-Sector Test: given a target, a direction sensor can identify whether it is in its certain sector or not.

Problem Statement

- Maximum Coverage with Minimum Sensors (MCMS) Problem
  - Given: a set of m static targets to be covered, a set of n homogenous directional sensors and each sensor with p possible orientations.
  - Problem: Find a minimum number of directional sensors with appropriate directions that maximize the number of targets to be covered.
- Theorem 3.1: MCMS is **NP-hard**.

Integer Linear Programming Formulation for MCMS Problem

$$\max \sum_{k=1}^{m} \Psi_k - \rho\left(\sum_{i=1}^{n}\sum_{j=1}^{p} X_{ij}\right)$$

Subject to

$$\frac{\xi_k}{n} \le \Psi_k \le \xi_k \forall k = 1 \ldots m$$

$$\sum_{j=1}^{p} X_{ij} \le 1 \forall i = 1 \ldots n$$

$$\Psi_k = 0 \text{ or } 1 \forall k = 1 \ldots m$$

$$X_{ij} = 0 \text{ or } 1 \forall i = 1 \ldots n, j = 1 \ldots p$$

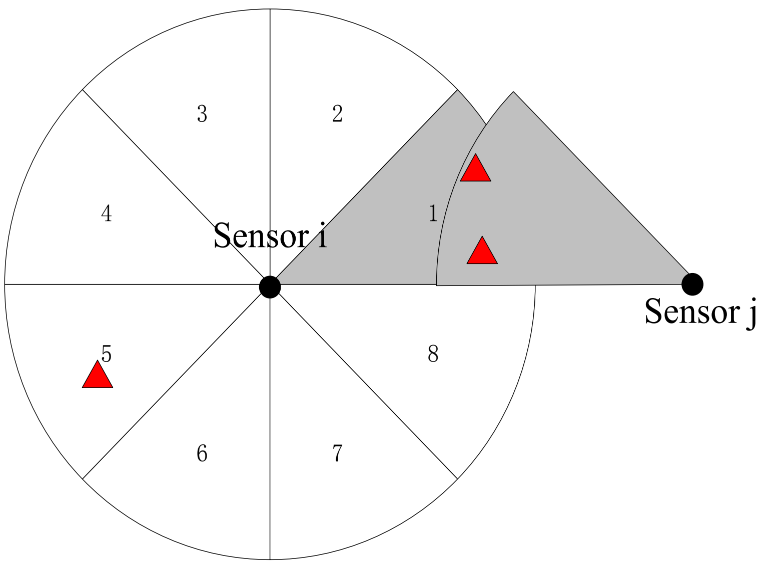
Integer Linear Programming Formulation for MCMS Problem (cont.)

- Bi-Objective function
  - a weighted sum of two conflicting objectives
  - i.e., max # of targets to be covered –[illegible]* # of sensors to be activated (the penalty coefficients [illegible] is a small number close to zero)
- Constraints
  - Every target k is covered by any sensor or not
  - One sensor can take at most one orientation
  - Other integer constraints
- ILP is utilized as a baseline to the distributed solution discussed later.

Distributed Greedy Algorithm (DGA)

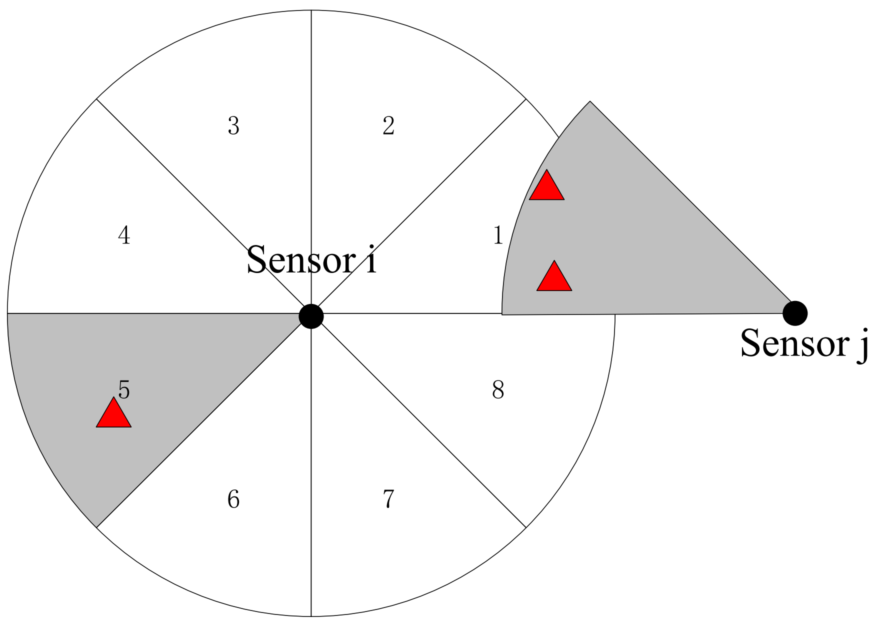
- Basic idea: utilize local exchanged information to coordinate nodes' behavior based on greedy heuristic.
  - i.e., a sensor intends to cover as many as possible targets
- Assumptions of DGA
  - Homogenous
  - Connected topology
  - Communication error-free

DGA (Alg.1) Performed on Sensor i



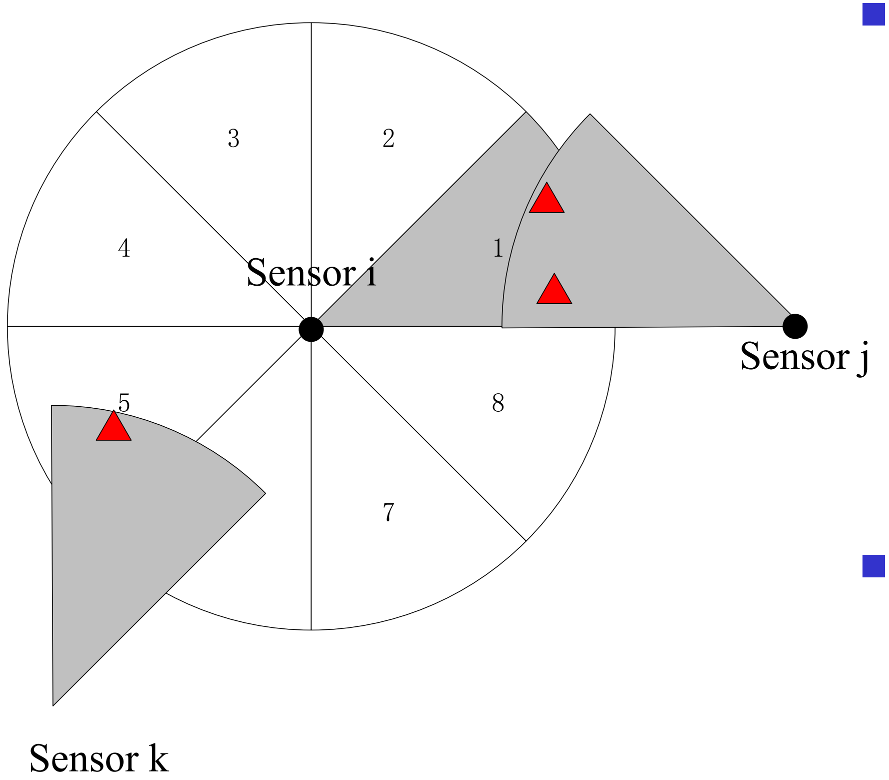
- Sensor i receives a coverage message sent by its sensing neighbor (e.g., sensor j)
  - **Coverage message**: <sensor id,location,orientation,priority>
  - **Priority**: a distinct value assigned to the sensor (e.g., a hash function value of sensor id)
  - ***Acquired targets*** of sensor i: not covered by any sensors with higher priority.
- Depending on information carried in the coverage message, sensor i computes the number of acquired targets in its every orientation
  - If $p_i > p_j$, then sector_1:**2** and sector_5:**1**
  - If $p_i < p_j$, then sector_1:**0** and sector_5:**1**

DGA Performed on Sensor i (cont.)



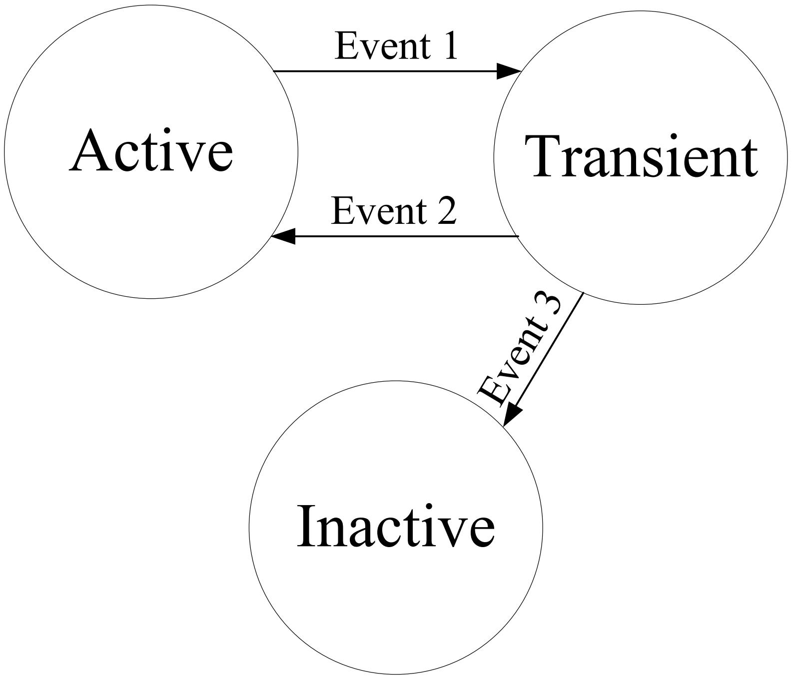
- Suppose $p_i < p_j$, applying the greedy principle of maximizing the number of acquired targets, sensor i switches to orientation 5 and then sends a coverage message as well to updating its state in sensing neighborhood.

DGA Performed on Sensor i (cont.)



- Suppose another sensor k with higher priority (than sensor i) covers the target as shown in the figure [left] while other settings remain the same.
- No acquired target available for sensor i, what should it do?
  - Ans: sensor i enters the "Transient" state

DGA Performed on Sensor i (cont.)



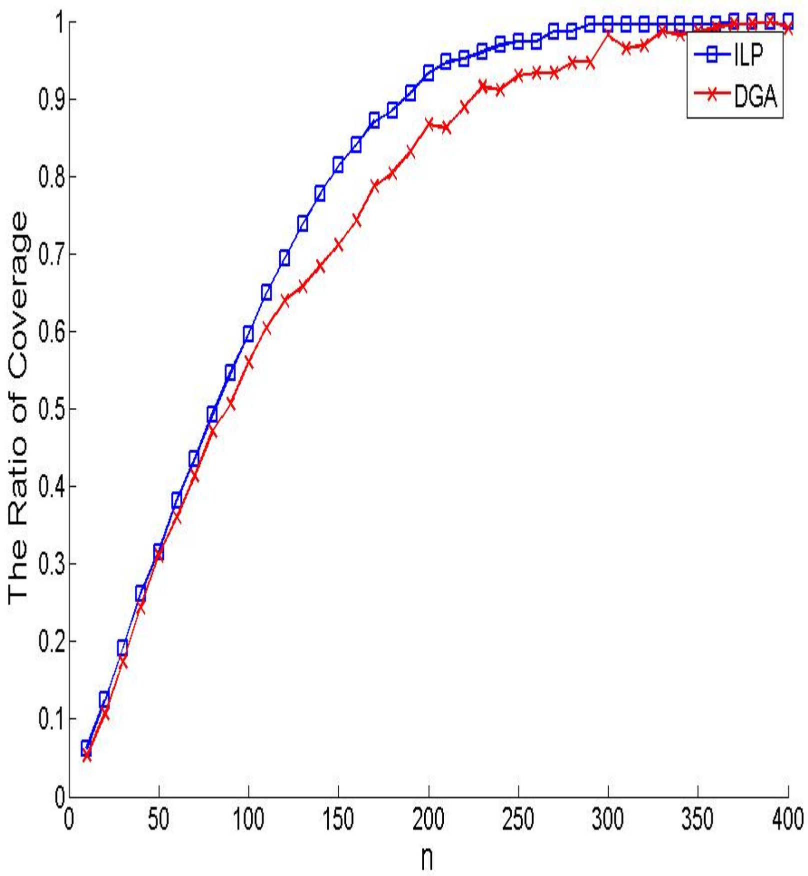
State transition diagram for sensor i

- **Event 1**: Active→Transient
  - If i discovers that no. of the acquired targets is zero
  - i triggers a transition timer T_w
- **Event 2**: Transient→Active
  - Acquired targets becomes non-zero before running out of T_w
  - Turn off timer
  - Switch its orientation to cover acquired target(s) accordingly
- **Event 3**: Transient → Inactive
  - T_w expires

DGA Properties

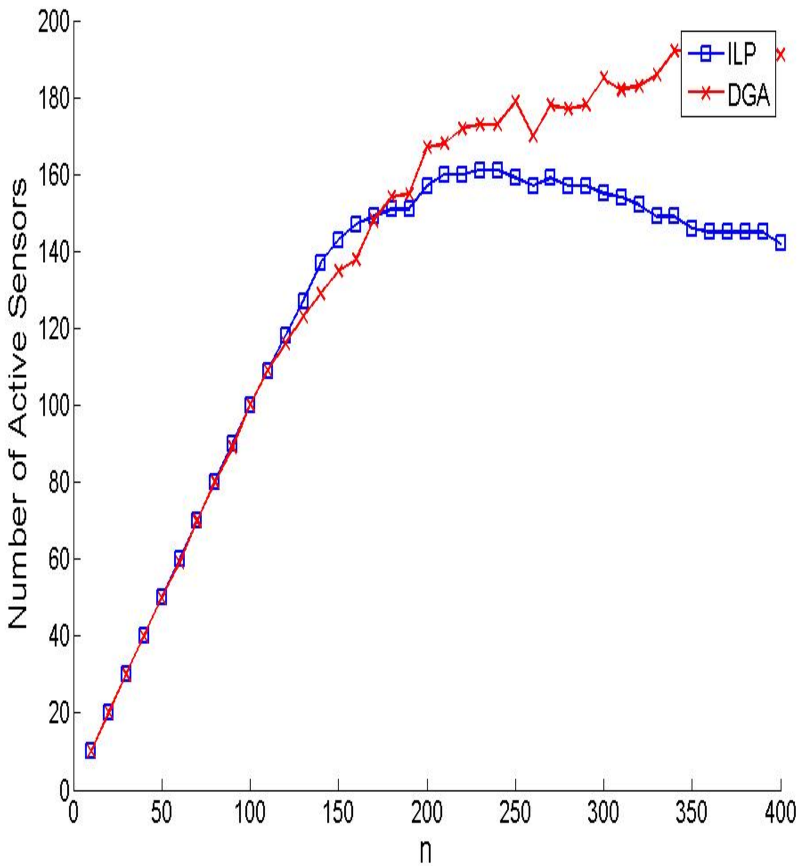
- DGA terminates in finite time (Theorem 5.1)
  - The higher priority of the sensor, the faster it reaches a final decision.
  - Time complexity is bounded by $O(n^2)$.
- DGA guarantees no "hidden" targets (Theorem 5.2)
  - Hidden targets: any target which is left uncovered because of a "misunderstanding," where one sensor assumes other sensor has covered the target, while it actually has not.

MCMS Problem solutions by ILP and DGA



- Given a fixed number of targets, varying the number of deployed directional sensors in the area.
  - Coverage ratio of ILP and DGA match closely for small or large *n*.
  - When *n* is in the middle range, coverage ratio of DGA is less than ILP (within 10%).

MCMS solutions by ILP and DGA (cont.)

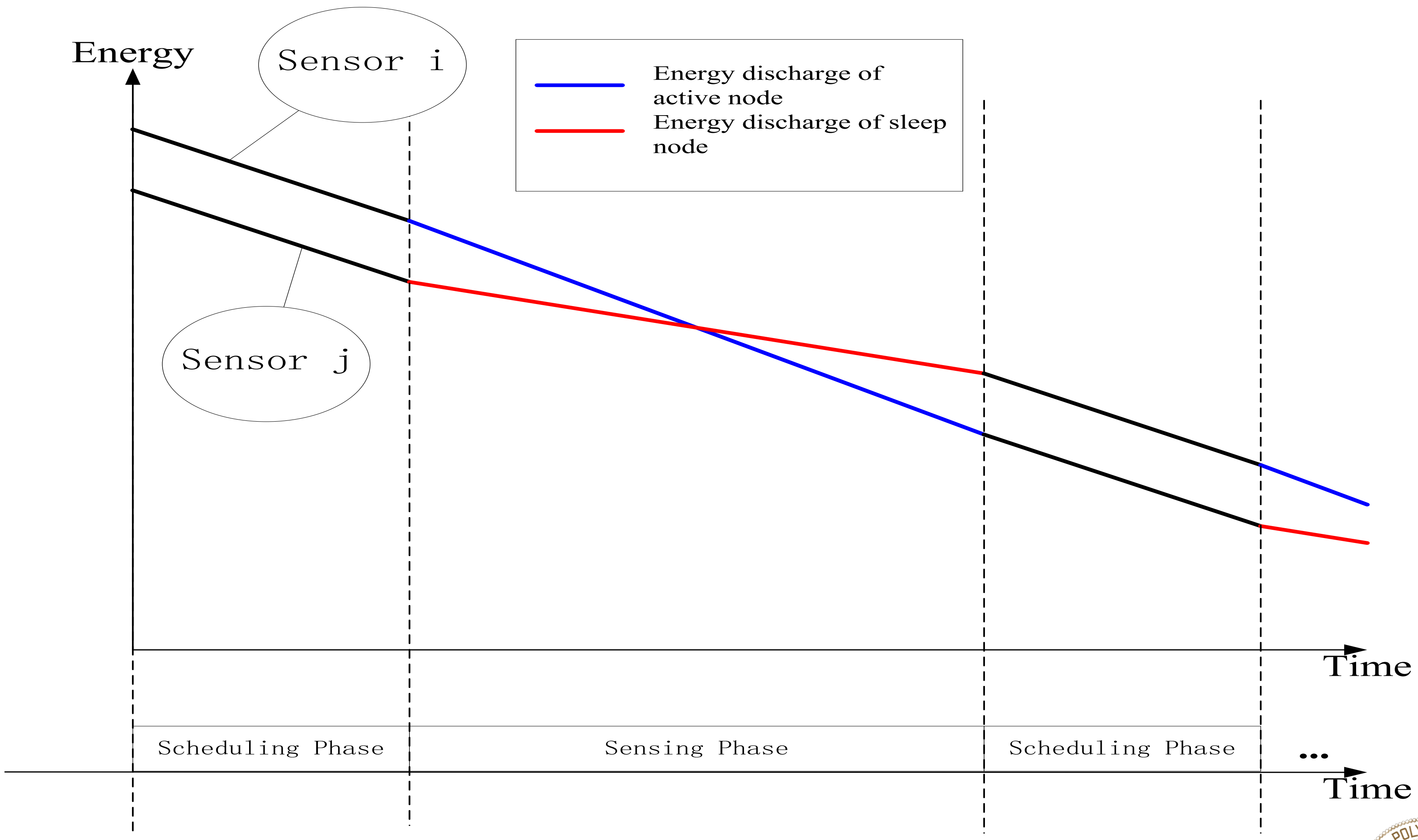


- Active node ratio of ILP and DGA match closely for small *n*.
- However, active node ratio of DGA exceeds that of ILP for large *n*.
  - It makes sensor that DGA depends only on local information.

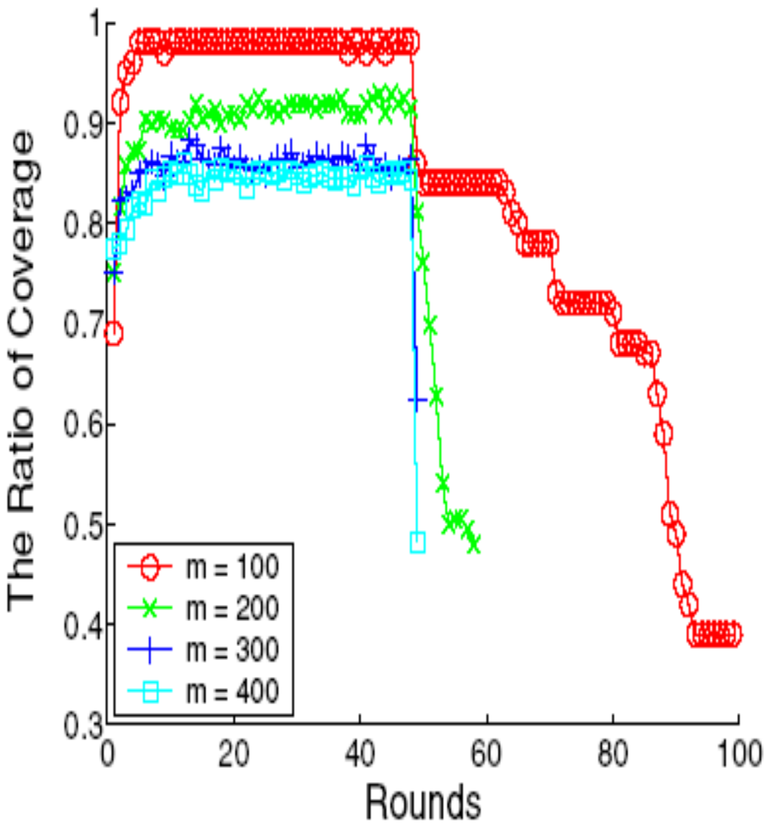
Sensing Neighborhood Cooperative Sleeping (SNCS) Protocol

- Motivation
  - The solution of MCMS problem is static and does not consider energy balancing among nodes.
- Basic idea of SNCS
  - Divide time into rounds and each round contains a (short) scheduling and (long) sensing phases.
  - Associate nodes' priorities with nodes' energy at the beginning of each scheduling phase to run DGA.

SNCS Protocol (cont.)



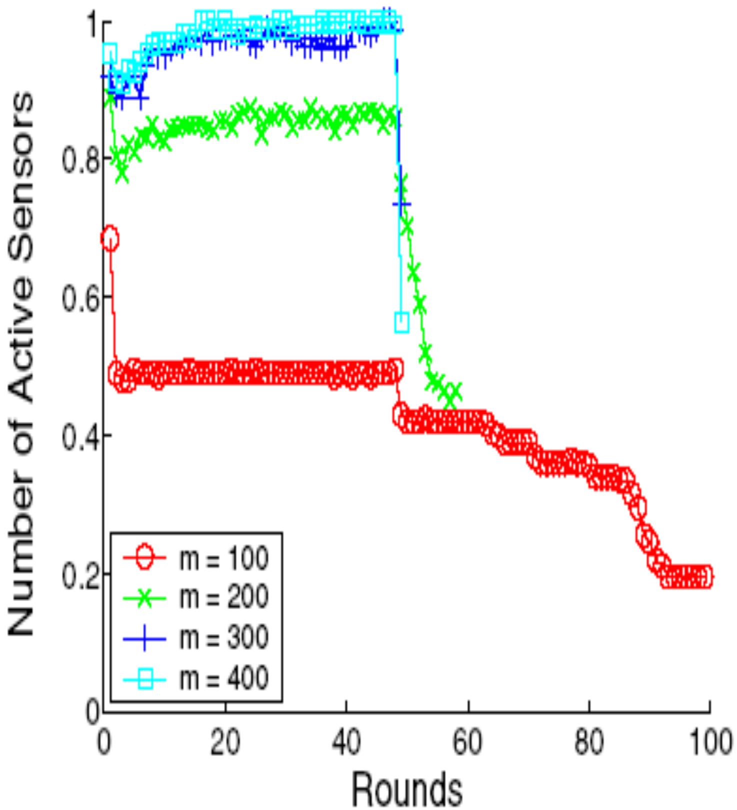
Performance of SNCS



(a) The ratio of coverage.

- Given a number of deployed directional sensors, vary the number of targets in the area
  - The smaller the *m*, the higher the coverage ratio
  - No matter what *m*, coverage ratio drops sharply after a certain time.

Performance of SNCS (cont.)



(b) The ratio of active.

- The less the *m*, the smaller the active node ratio
- No matter what *m*, active node ratio drops sharply after a certain time.

Robustness of SNCS

	Coverage ratio	Active nodes ratio
Location errors	*decreases*	*constant*
Orientation errors	*decrease*	*constant*
Communication errors	*constant*	*increase*

Conclusions

- Formulate a combinatorial optimization problem on coverage of discrete targets by directional sensors (i.e., MCMS problem).
- Provide an exact centralized ILP solution and distributed greedy algorithm of MCMS problem.
- Design a coverage-optimal and energy-efficient protocol based on DGA (i.e., SNCS protocol).
- Performance evaluations show the effectiveness and robustness of SNCS protocol.

Thank you!

- Questions?