

Coverage by Directional Sensors

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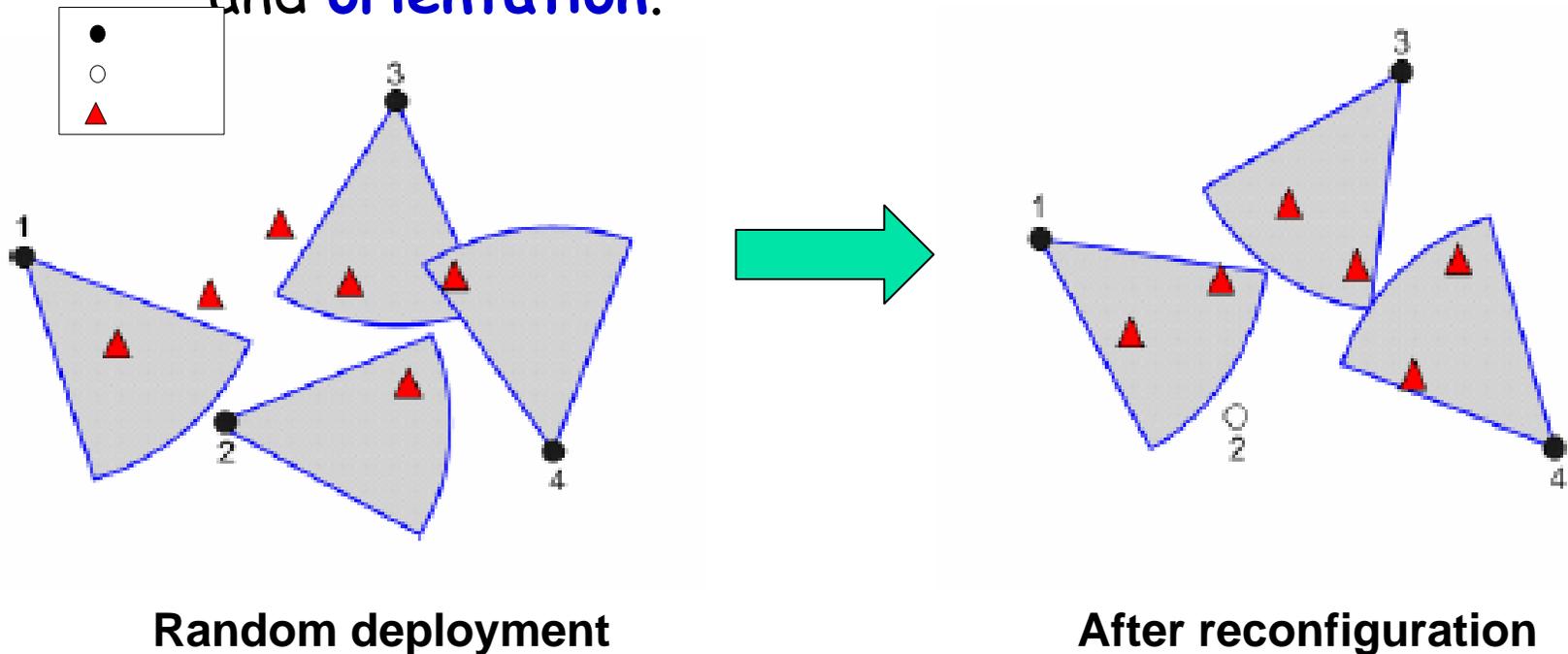
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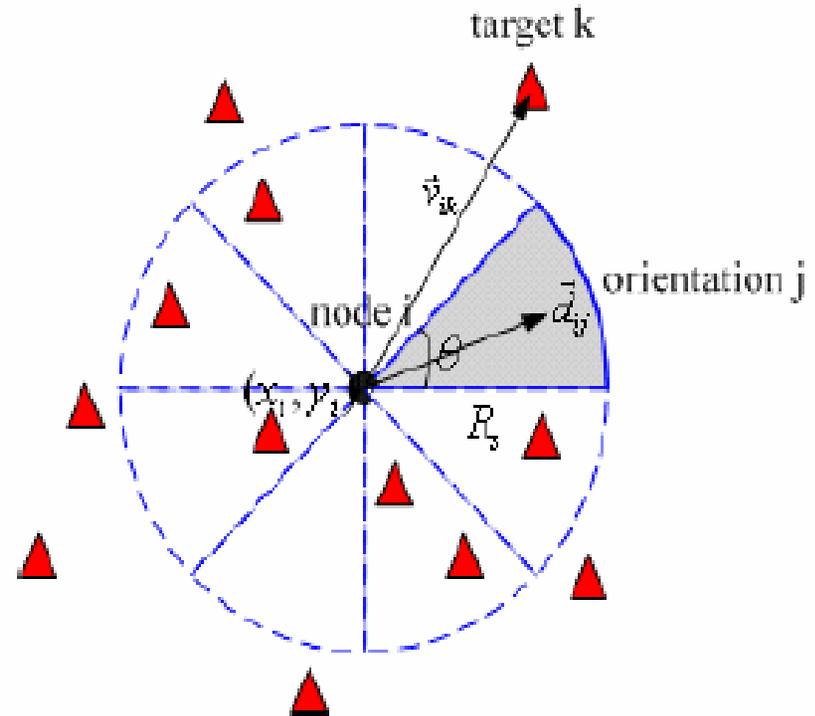
Motivation

- 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**.



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

$$\frac{\xi_k}{n} \leq \Psi_k \leq \xi_k \quad \forall k = 1 \dots m$$

$$\sum_{j=1}^p X_{ij} \leq 1 \quad \forall i = 1 \dots n$$

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

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

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 $-\rho^*$ # of sensors to be activated (the penalty coefficients ρ 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.



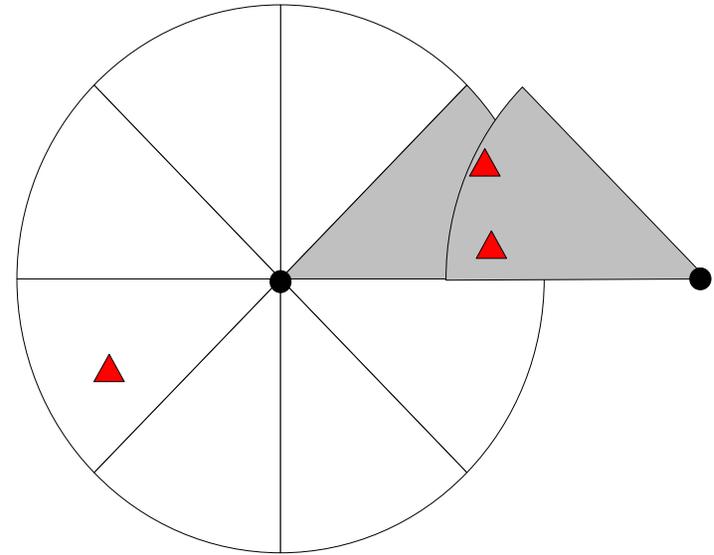
Distributed Greedy Algorithm (DGA)

- 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

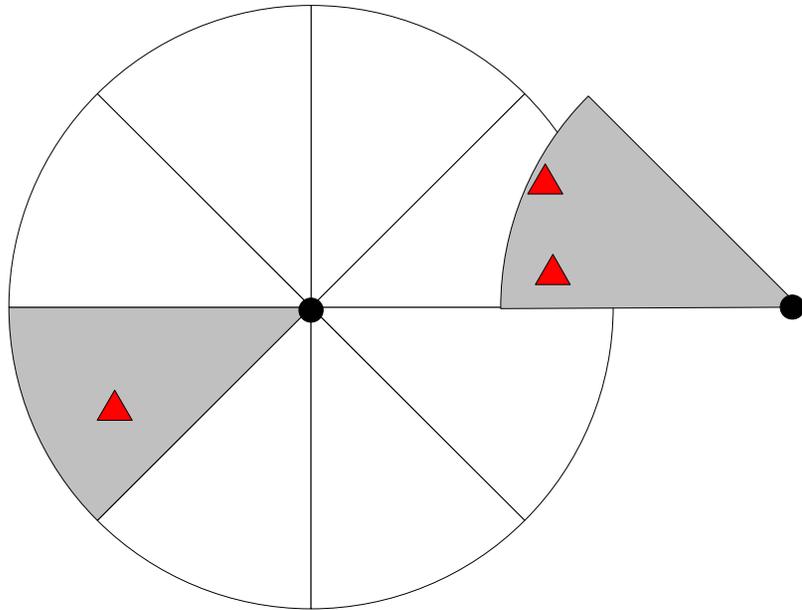


DGA (Alg.1) Performed on Sensor i

- 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

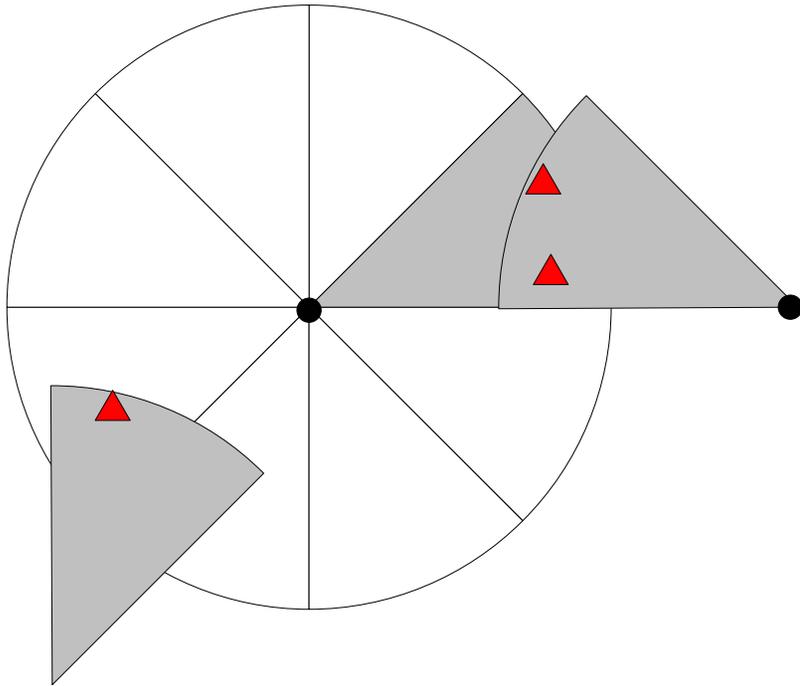


DGA Performed on Sensor i (cont.)



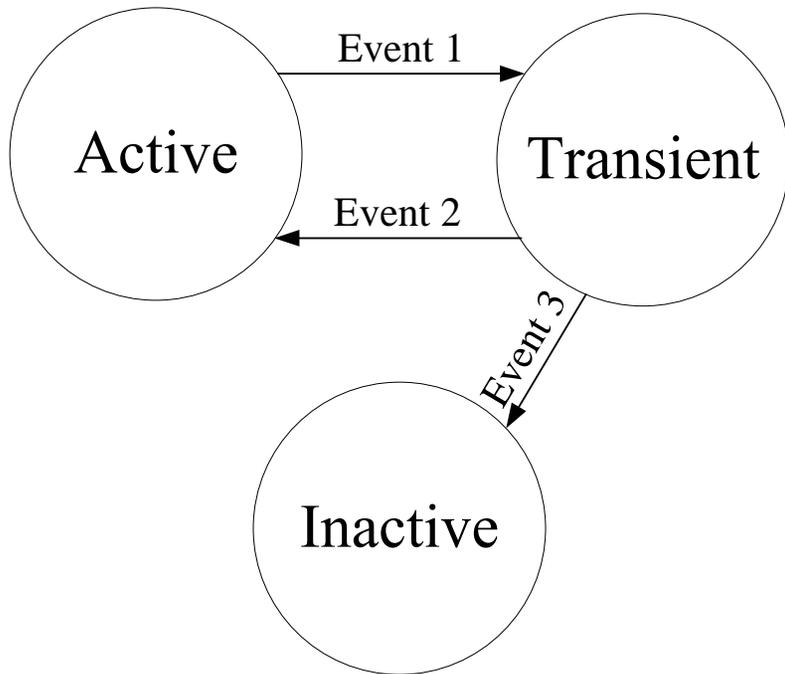
- Suppose $p_i < p_j$, applying the greedy principle of maximizing the number of acquired targets, sensor i switches to orientation 5 and then sends a coverage message as well to updating its state in sensing neighborhood.

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

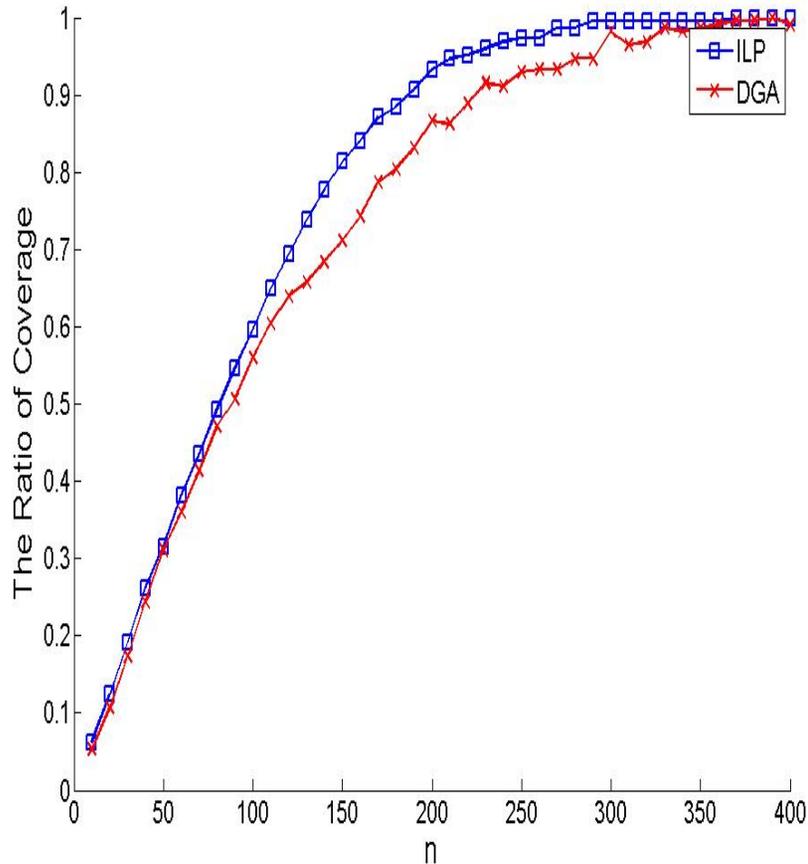
- **Event 1: Active \rightarrow Transient**
 - If i discovers that no. of the acquired targets is zero
 - i triggers a transition timer T_w
- **Event 2: Transient \rightarrow Active**
 - Acquired targets becomes non-zero before running out of T_w
 - Turn off timer
 - Switch its orientation to cover acquired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

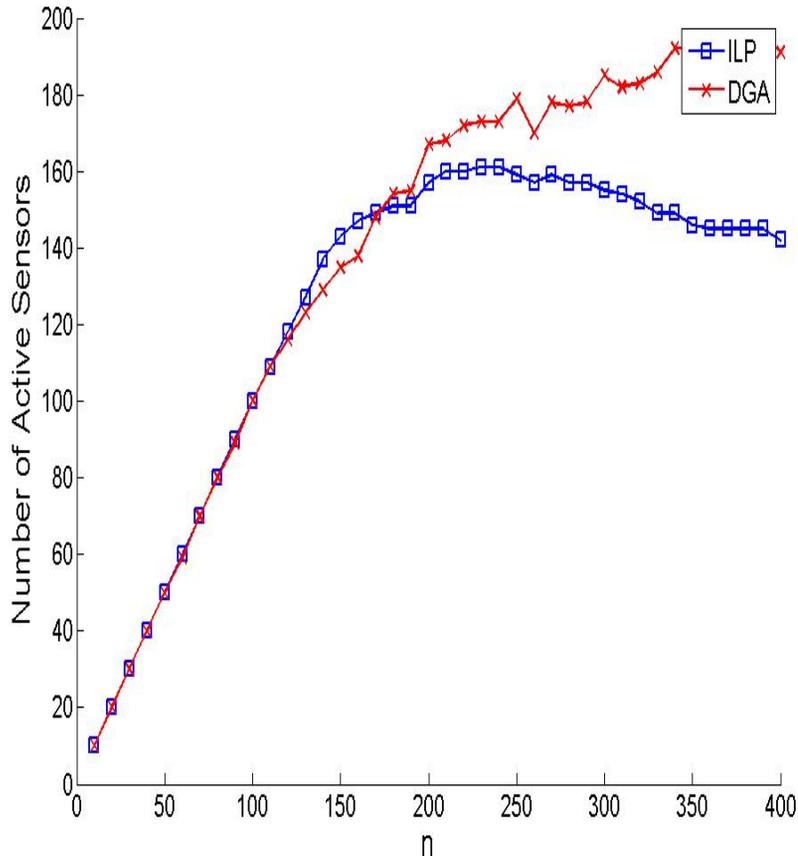


MCMS Problem solutions by ILP and DGA



- 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.)



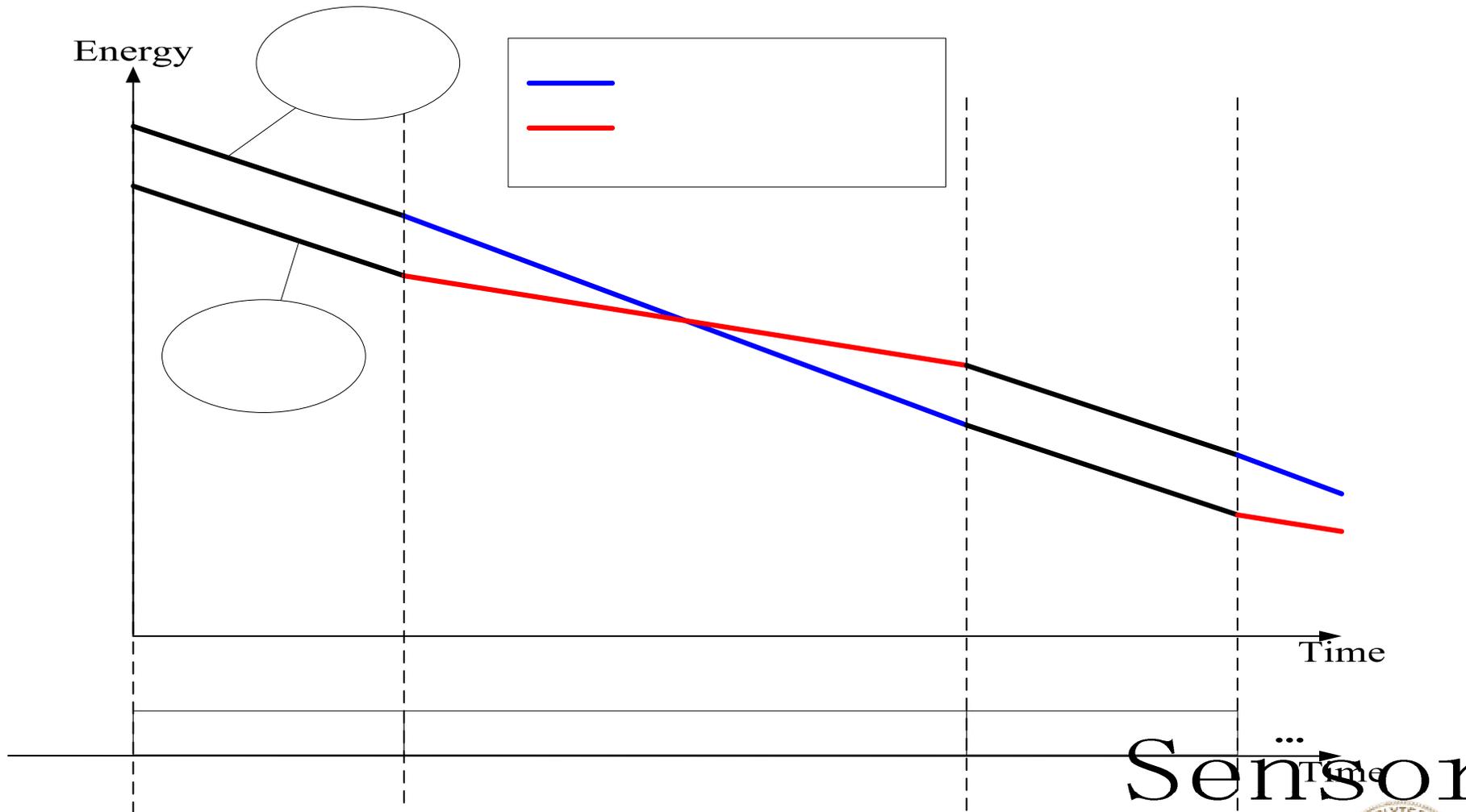
- Active node ratio of ILP and DGA match closely for small n .
- However, active node ratio of DGA exceeds that of ILP for large n .
 - It makes sense that DGA depends only on local information.

Sensing Neighborhood Cooperative Sleeping (SNCS) Protocol

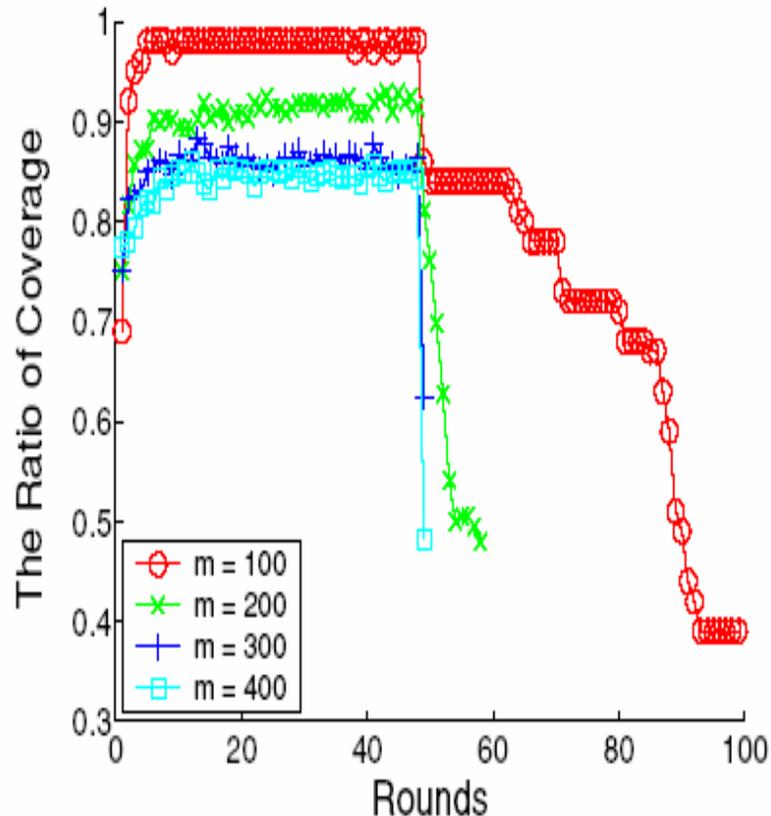
- Motivation
 - The solution of MCMS problem is static and does not consider energy balancing among nodes.
- Basic idea of SNCS
 - Divide time into rounds and each round contains a (**short**) scheduling and (**long**) sensing phases.
 - Associate nodes' priorities with nodes' energy at the beginning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



SNCS Protocol (cont.)



Performance of SNCS

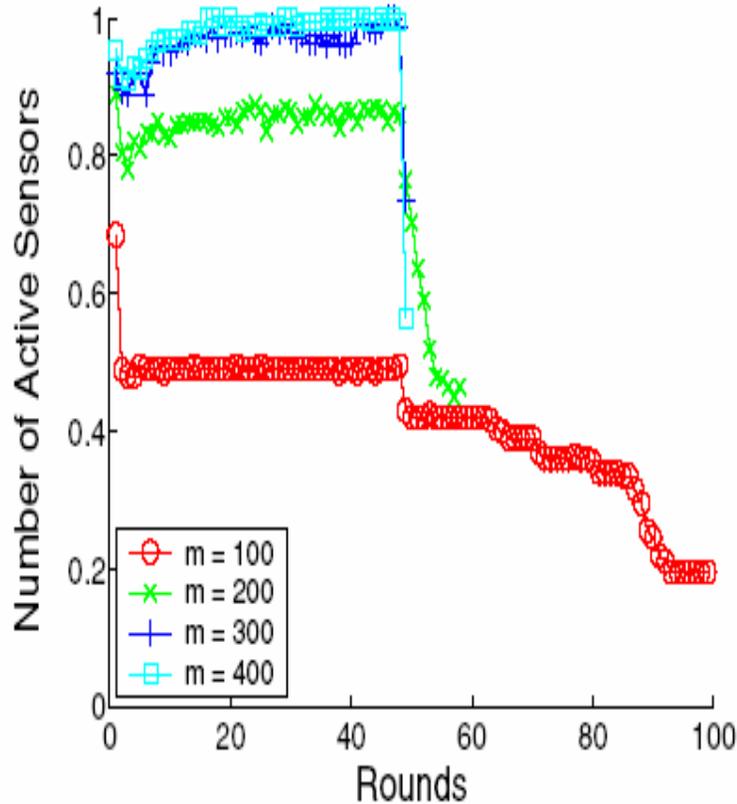


(a) The ratio of coverage.

- 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.)

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



(b) The ratio of active.

Robustness of SNCS

	Coverage ratio	Active nodes ratio
Location errors	<i>decreases</i>	<i>constant</i>
Orientation errors	<i>decrease</i>	<i>constant</i>
Communication errors	<i>constant</i>	<i>increase</i>

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?

