



Coverage in Sensor Networks

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ECSE 6962



Coverage problems

- Definition: the measurement of quality of service (surveillance) that can be provided by a particular sensor network

Coverage problems can be classified in three types

- **Area coverage**

the main objective is to cover an area

- **Point coverage**

the objective is to cover a set of targets

- **Detectability**

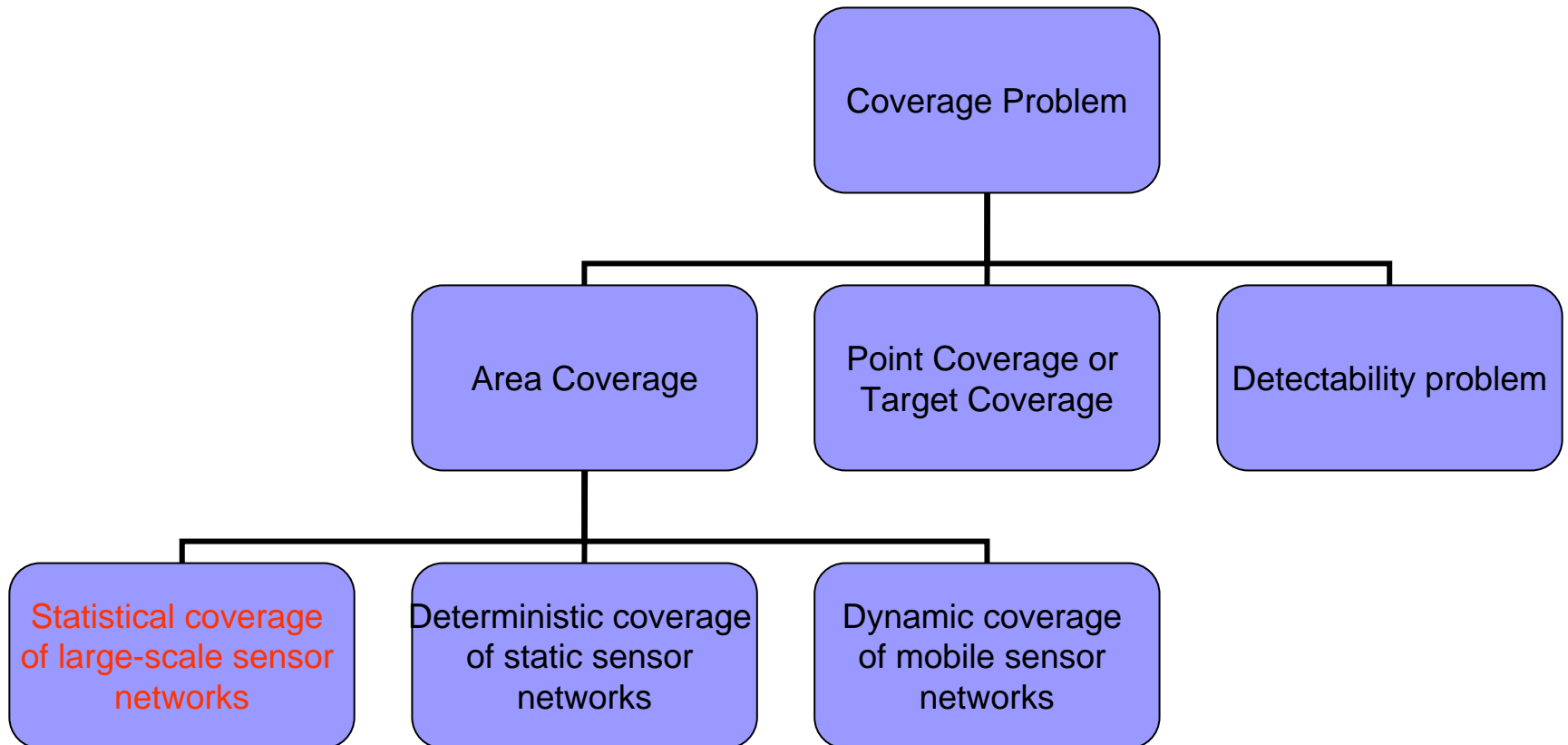
an objective to determine the maximal support/breach paths that traverse a sensor field



Area coverage includes three viewpoints

- Statistical coverage of large-scale sensor networks
- Deterministic coverage of static sensor networks
- Dynamic coverage of mobile sensor networks

Structure of my lecture presentation



Statistical coverage of large-scale sensor networks

- Character the followings by studying the fundamental property and limitation of a sensor networks' coverage:
 - Area coverage (f_a): the fraction of the geographic area covered by sensors
 - Node coverage fraction (f_n): the fraction of sensors that can be removed without reducing covered area

Location model

the locations of sensors are a uniformly and independently two-dimensional Poisson point process with density parameter λ :

$$P(N(A) = k) = \frac{e^{-\lambda\|A\|} (\lambda\|A\|)^k}{k!}$$

Sensing model

1) Boolean sensing model:

each sensor has a certain sensing range r and a location is said to be covered if it lies within the sensor's sensing range

2) General sensing model:

$$S(s, p) = \begin{cases} \frac{\alpha}{d(s, p)^\beta} & A \leq d(s, p) < B \\ 0 & \text{otherwise} \end{cases} \quad I_p = \sum_{i=1}^{\infty} S(s_i, p) = \sum_{i=1}^{\infty} \frac{\alpha}{d(s_i, p)^\beta}$$

a point is covered if the all-sensor field intensity at p is greater than or equal to some threshold θ

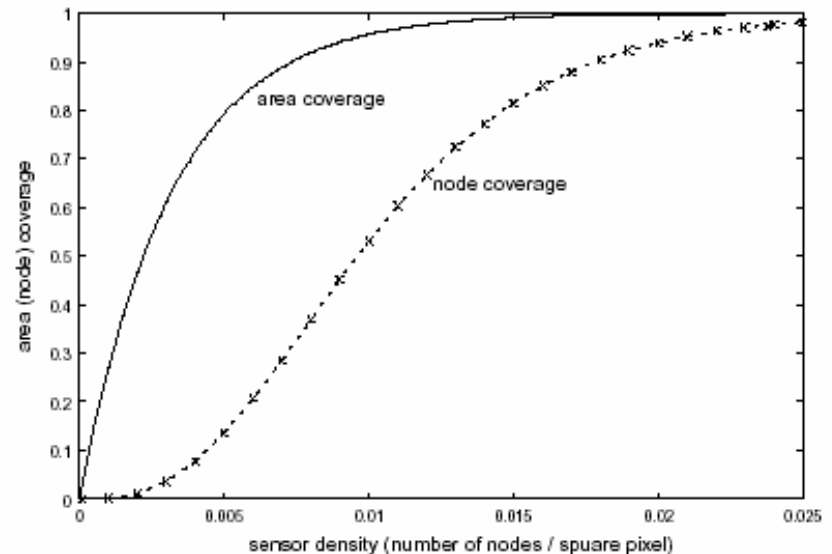
Results of Boolean sensing model

- for a two-dimensional infinite plane, the area coverage of such a sensor network is

$$f_a = 1 - e^{-\lambda \pi r^2}$$

$$\lambda = -\ln(1 - f_a) / \pi r^2$$

- difficult to obtain a closed form expression for node coverage



Results of general sensing model

- the area coverage

$$f_a = P(I_p \geq \theta) = \int_{\theta}^{\infty} f_{I_p}(x) dx$$

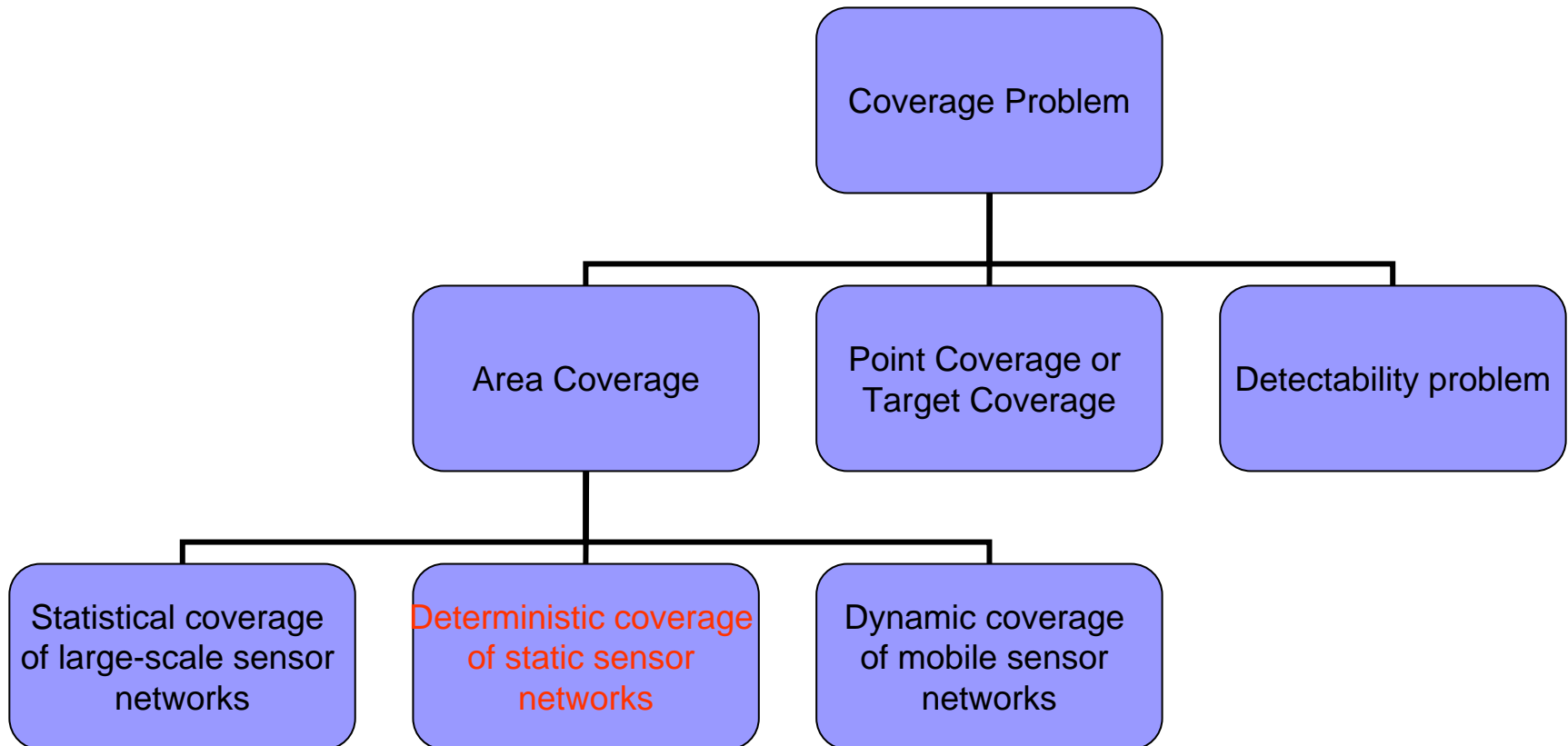
for the special case $\beta = 4$

$$f_{I_p}(x) = \frac{\lambda \pi \alpha^{1/2}}{2} x^{-3/2} \exp\left[-\frac{\lambda^2 \pi^3 \alpha}{4x}\right]$$

$$f_a = \int_{\theta}^{\infty} f_{I_p}(x) dx = 1 - \frac{1}{\sqrt{\pi}} \Gamma\left(\frac{1}{2}, \frac{\alpha \lambda^2 \pi^3}{4\theta}\right)$$

- In the general sensing model, no sensor can be turned off without reducing the covered region, or $f_n = 0$

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Topics in deterministic coverage of static sensor networks

- aims at energy conservation
switch some redundant sensors to sleeping state
- how to efficiently select the active node that must maintain both sensing coverage and network connectivity

Coverage degree and connectivity degree of a graph or region

■ Definition of coverage degree

a convex region A has a coverage degree of K if every location inside A is covered by at least K nodes

■ Definition of connectivity degree

if a graph is K -connected, then for any possible $k \leq K$ active nodes which fail the sensor network will remain connected

Goals in static sensor network

- Given a coverage region A and a node coverage degree K , the goal of an integrated coverage and connectivity configuration is to maximize the number of nodes that are scheduled to sleep under the constraints that the remaining nodes must guarantee:
 - 1) A is at least K -covered
 - 2) All active nodes are connected

Relationship between degree of coverage and connectivity

- Theorem 1:

for a set of nodes that at least 1-cover a convex region A , the communication graph is connected if $R_c \geq 2R_s$

- Theorem 2:

a set of nodes that k -cover a convex region A forms a k -connected communication graph if

$$R_c \geq 2R_s$$



continued

Theorem 3 (determining the coverage degree):

a convex region A is k -covered by a set of nodes if 1) there exist in region A intersection points between nodes or between nodes and A 's boundary; 2) all intersection points between any nodes are at k -covered; and 3) all intersection points between any node and A 's boundary are at least K -covered

K-Coverage Eligibility Algorithm

Given a requested coverage degree K , a node is ineligible if every location within its coverage range is already K -covered by other active nodes in its neighborhood.



Coverage configuration protocol (CCP)[xw05]

Each node determines its eligibility using the K-coverage eligibility algorithm based on the information about its sensing neighbors, and may switch state dynamically when its eligibility changes.

Key benefits of CCP:

- 1) CCP can configure a network to the specific coverage degree requested by the application
- 2) It is a decentralized protocol that only depends on local states of sensing neighbors

Shortcoming of CCP:

It does not guarantee the scheduling of sensors is optimal and also does not give the comparison and analysis of the gap between CCP and optimal solution

the optimal solution of coverage problem of static sensor networks

■ Assumption

- 1) Represent the surveillance field by a 2D grid, there are a total of m grid points in the field $G = \{g_1, g_2, \dots, g_m\}$
- 2) Use S to denote the set of n sensor nodes $|S| = n$ that have been placed in the sensor field, each sensor referred as $s_k = (s_k \in S, 1 \leq k \leq n)$
- 3) d_i^k is the distance between sensor node S_k and grid point g_i
- 4) Use exponential function to represent the confidence level in the received sensing signal:
$$p_i^k = \begin{cases} e^{-\alpha d_i^k} & d_i^k \leq r_s \\ 0 & otherwise \end{cases}$$
- 5) S_i is the set of nodes that can detect g_i , i.e., $\forall s_k \in S_i, d_i^k \leq r_s$ thus, the detection probability for grid point g_i is evaluated by $p_i(S_i) = 1 - \prod_{s_k \in S_i} (1 - p_i^k)$

goal

- Only nodes in the subset need to be actively performing the sensing task and all grid points are still covered with detection probability no lower than p_{th}
- The optimization of this problem is to find such a subset with minimum size, i.e., the minimum number of nodes

Coverage-centric active nodes selection (CCANS)

■ Definition of CCANS

Given the parameter p_{th} , $0 \leq p_{th} \leq 1$, a set S of n sensor nodes, a set G of m grid points, find a subset $S_a \subseteq S$ such that, when only nodes in S_a are active,

1. $\forall g_i \in G$ and $S_i \subseteq S_a$, $p_i(S_i) \geq p_{th}$
2. $|S_a|$ is minimum
3. $\forall s \in S_a$ is connected

CCANS is *NP-complete* [ZC05]

CCANS can be solved using integer linear programming:


Objective: minimize $C = \sum_{k=1}^n x_k$

Subject to

$$1 - \prod_k^n (1 - x_k a_i^k p_i^k) \geq p_{th}, 1 \leq i \leq m$$

$$x_k = 0 \quad \text{or} \quad x_k = 1, 1 \leq k \leq n$$

$$a_i^k = 0 \quad \text{or} \quad a_i^k = 1, 1 \leq i \leq m, 1 \leq k \leq n$$



[ZC05] proposes a distributed (heuristic) approach for coverage-centric active node selection based on the formation of a connected dominating set

Comparing the distributed solution to an optimal solution obtained by integer linear programming (centralized approach):

The distributed approach performs almost as well as the centralized approach for large values of the sensing range

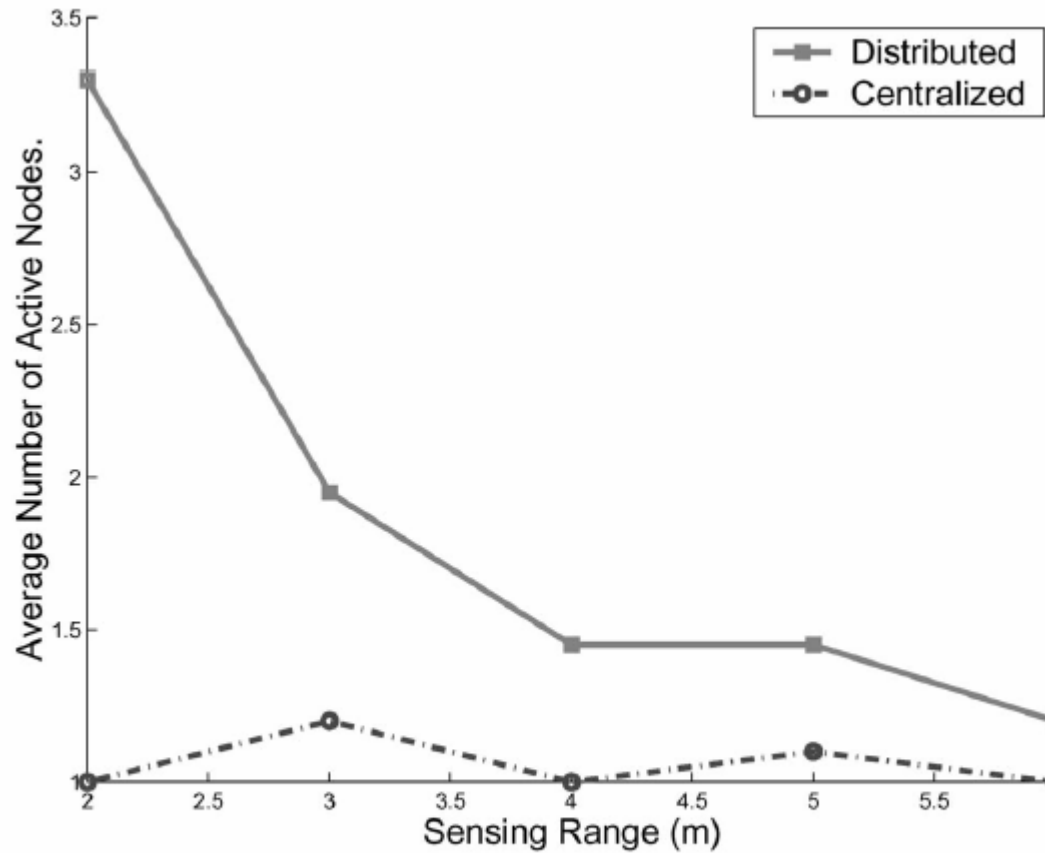
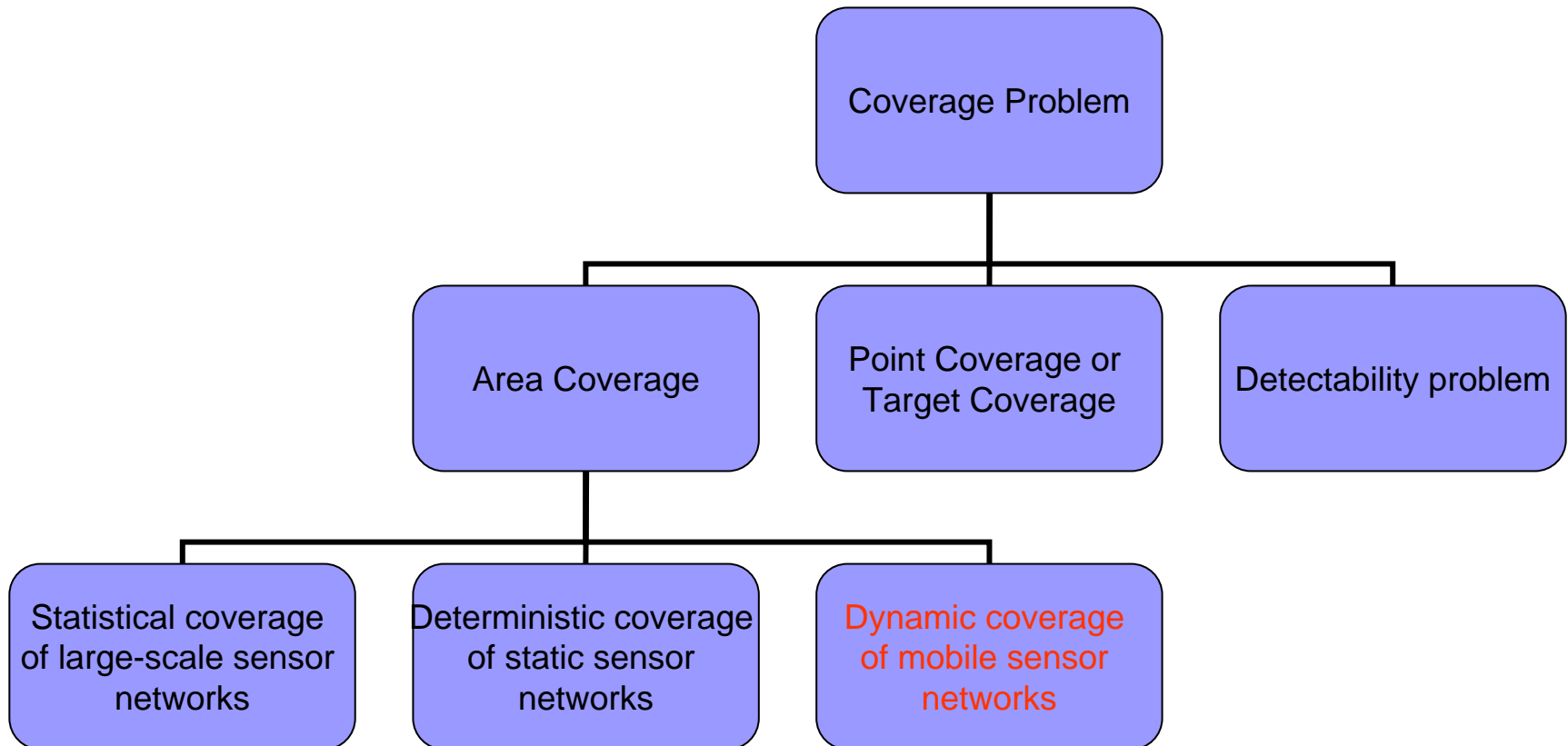



Fig. 11. Comparison of the number of active nodes determined using the centralized approach (ILP) and the distributed approach (CCANS).

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Dynamic Coverage Maintenance- mobile sensor networks

- Migration

 - the process of moving nodes for maintaining coverage

- Objective

 - how to compensate the coverage loss by migrating neighbor sensors when the failure of one sensor node leads to coverage loss

- Assumption

 - the transmission range is more than twice the sensing range

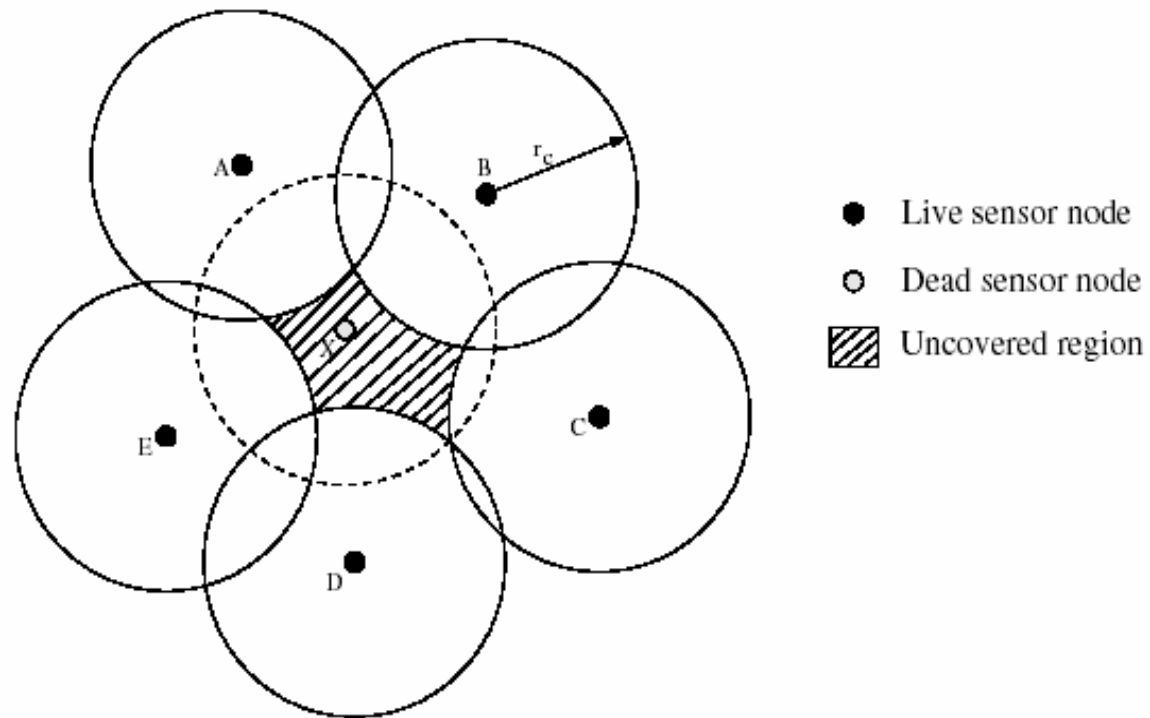


Figure 1. Loss of coverage due to a node's death.

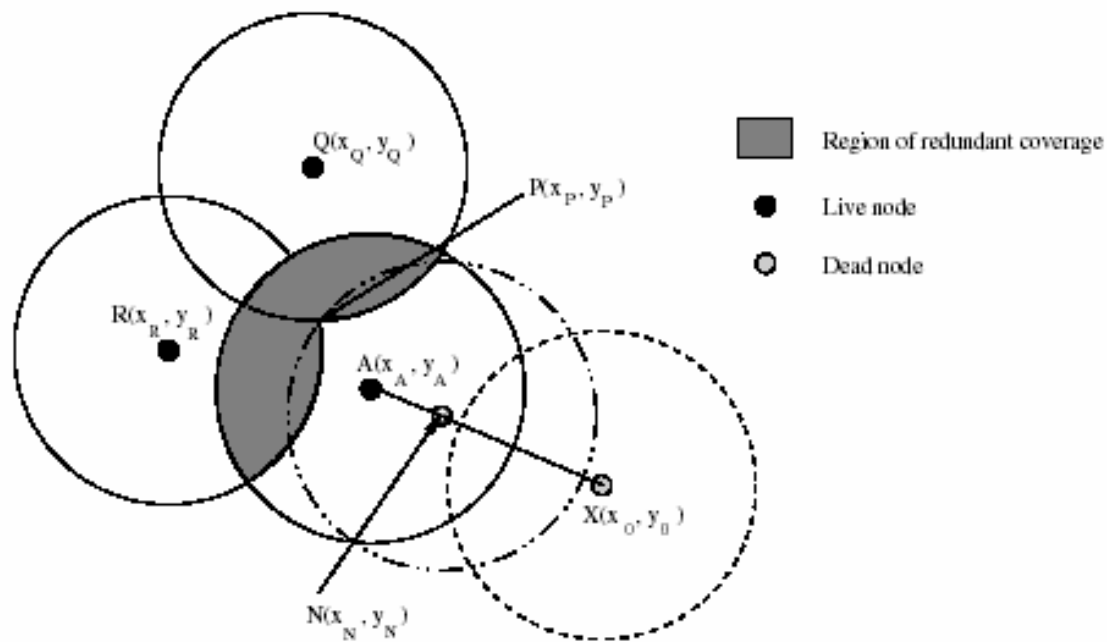


Figure 2. Determination of migration-end-point.

Formulated as optimization problem

- Let the dead node X have n neighbors A_1, A_2, \dots, A_n , and for each neighbor it has a restricted point P_i , P_1, P_2, \dots, P_n , the initial coverage of node X is $C_{init}(X)$. We need to move the neighbors to new position N_1, N_2, \dots, N_n towards X , such that the following conditions are satisfied.
 1. The area $C_{init}(X) \cap [C(N_1) \cup C(N_2) \cup \dots \cup C(N_n)]$ is maximum.
 2. $\sum_{i=1}^n A_i N_i$ is minimum.

the above problem is exponential complex

Several heuristic schemes [SM05]

- Maximum Energy Based (MEB)

prefer the migration of nodes which have a larger available energy

- Minmax Distance (MMD)

the neighbor which has to move the minimum of these distances is chosen

- Minimum D/E (MDE)

ordering the neighbors of a node based on the ratio of maximum distance they can move to their available energy

- Minimum Distance Lazy (MDL)

moving neighboring nodes so that the uncovered area is the most likely to be covered

Cascaded DCM Scheme

the four heuristic proposed so far move only the one-hop neighbors of the dead node to compensate the lost coverage. It is possible that an extension over n-hop neighbors may reduce the total expense of energy more efficiently

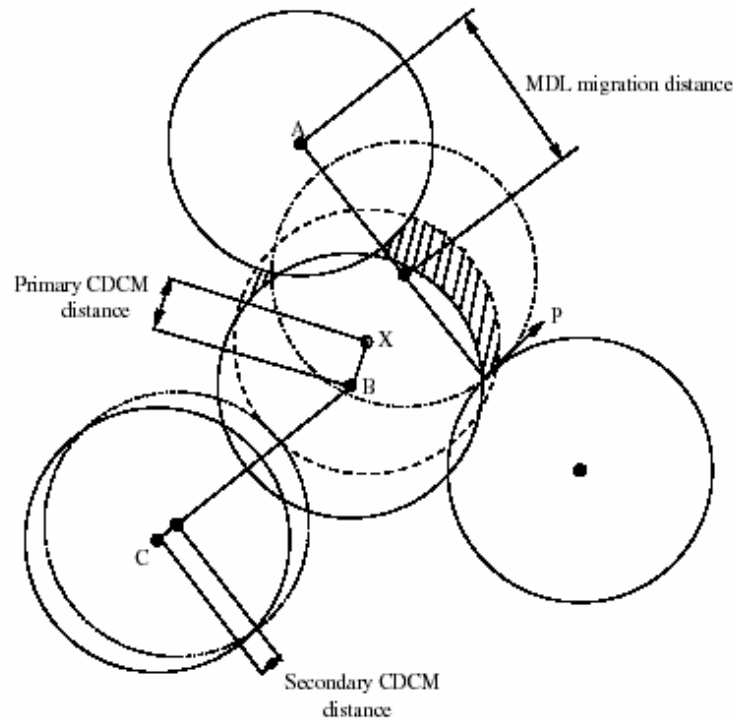
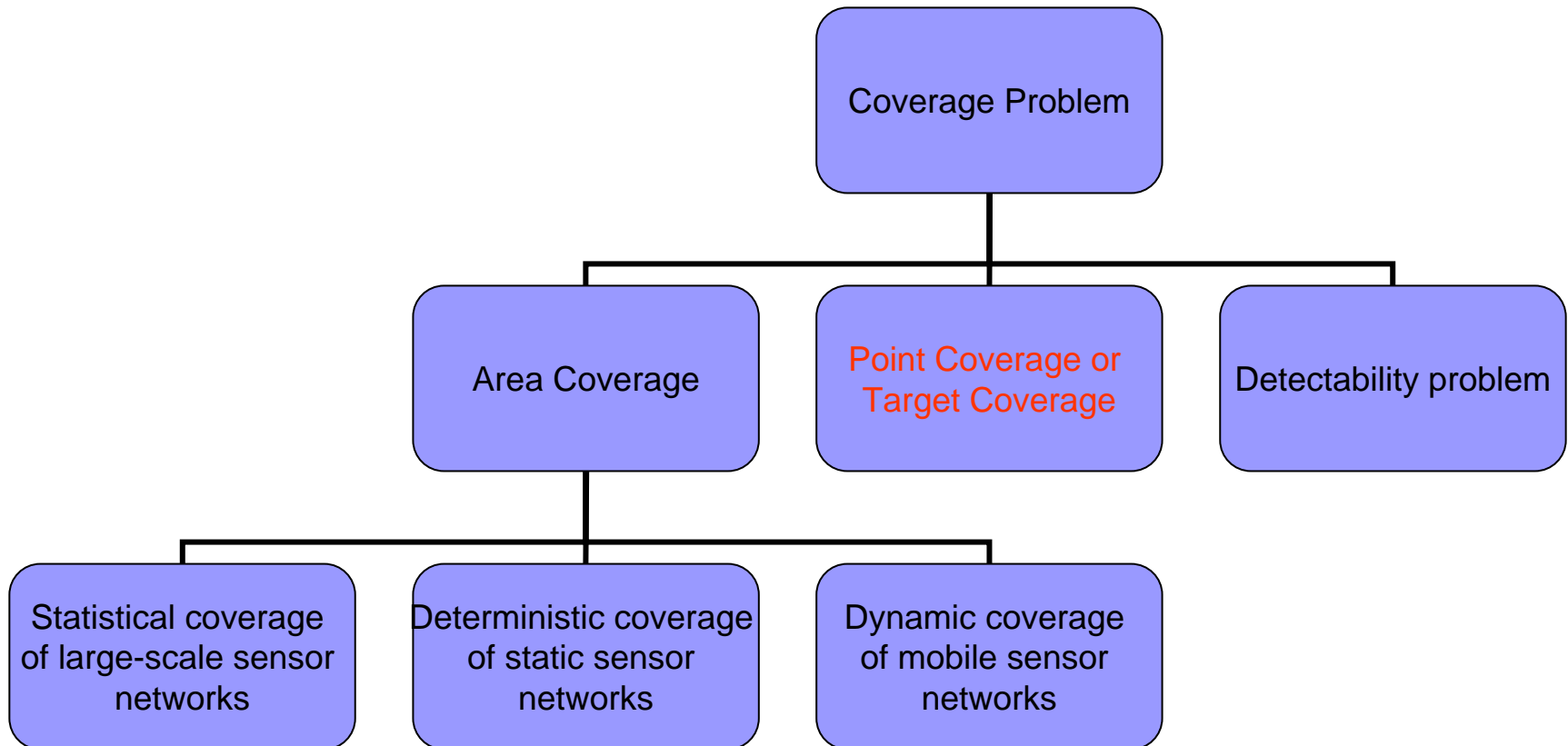


Figure 6. Cascaded DCM.

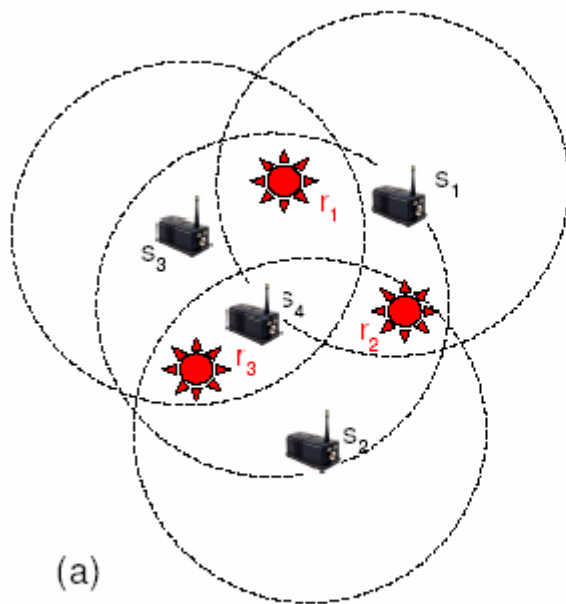
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Target coverage problem

- Objective and definition

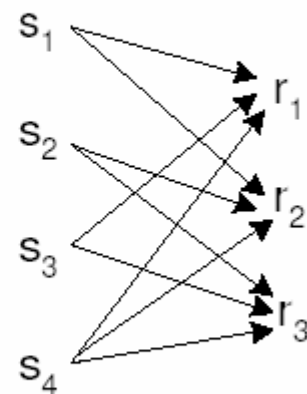
Given m targets with known location and an energy constrained wireless sensor network with n sensors randomly deployed in the closed proximity of the targets, schedule the sensor nodes activity such that all the targets are continuously observed and network lifetime is maximized



(a)

$$C = \{s_1, s_2, s_3, s_4\}$$

$$R = \{r_1, r_2, r_3\}$$



(b)

$$s_1 = \{r_1, r_2\}$$

$$s_2 = \{r_2, r_3\}$$

$$s_3 = \{r_3, r_1\}$$

$$s_4 = \{r_1, r_2, r_3\}$$

Maximum Set Covers (MSC) problem

■ Definition

Given a collection C of subsets of a finite set R , find a family of set covers S_1, \dots, S_p with time weights t_1, \dots, t_p in $[0, 1]$ such that to maximize $t_1 + \dots + t_p$ and for each subset s in C , s appears in S_1, \dots, S_p with a total weight of at most 1, where 1 is the life time of each sensor.

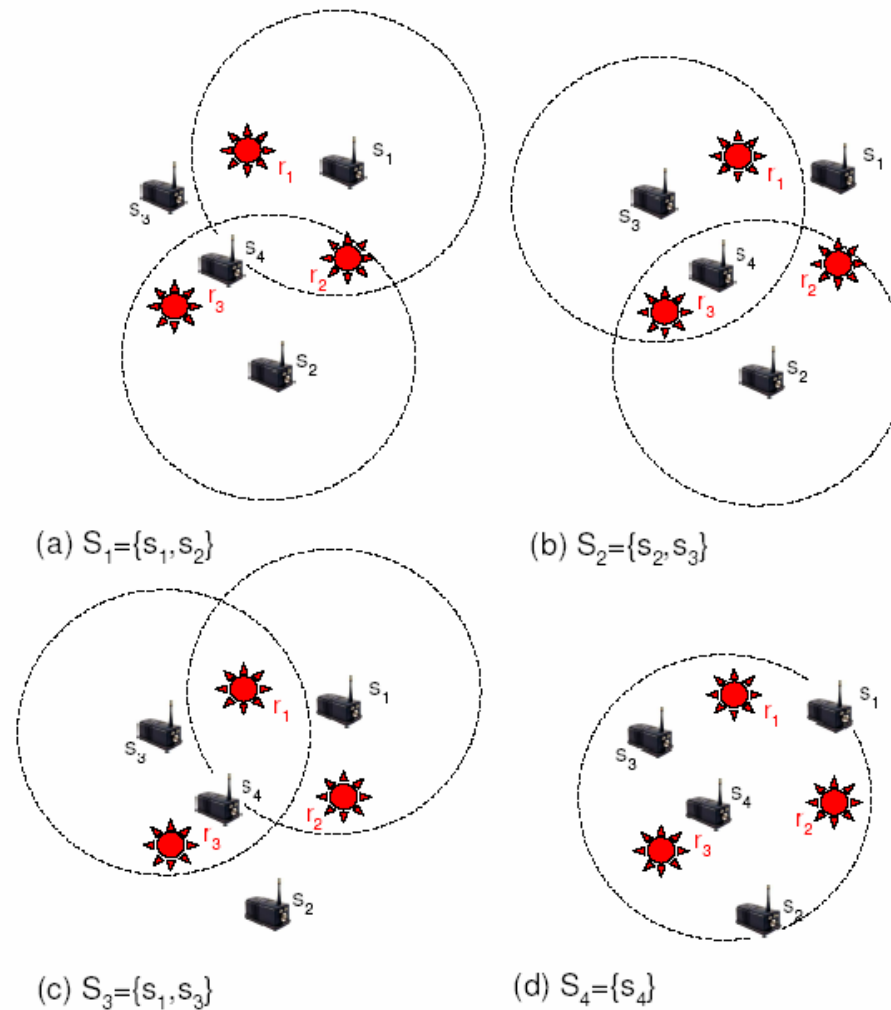
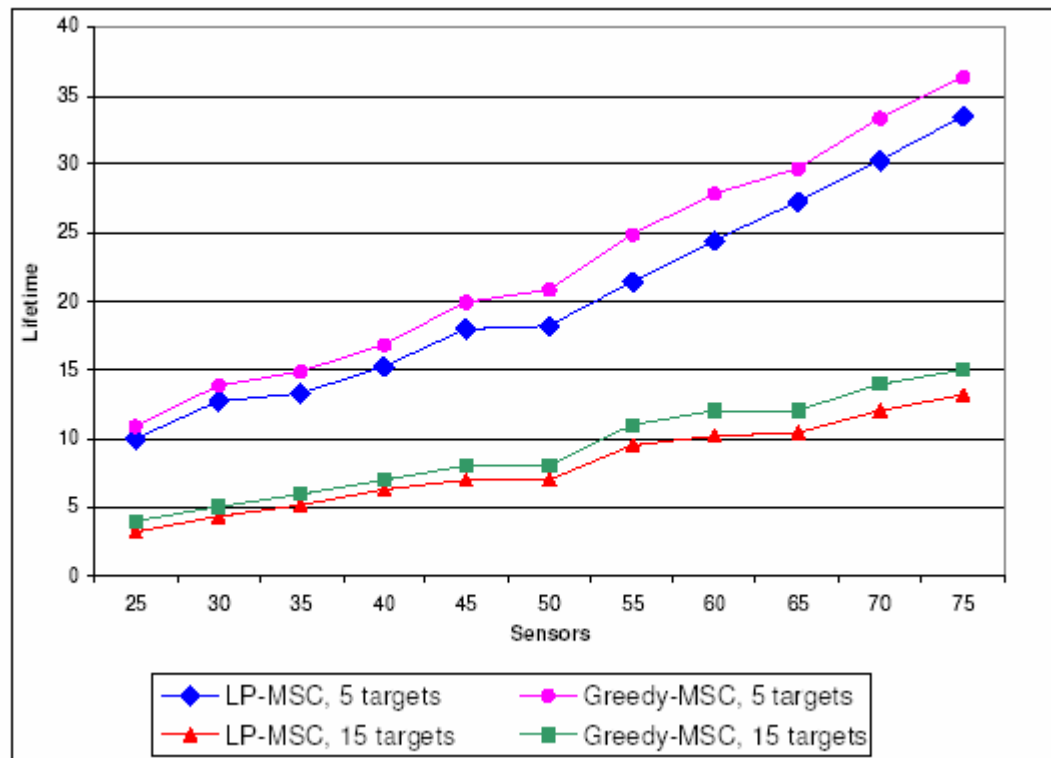


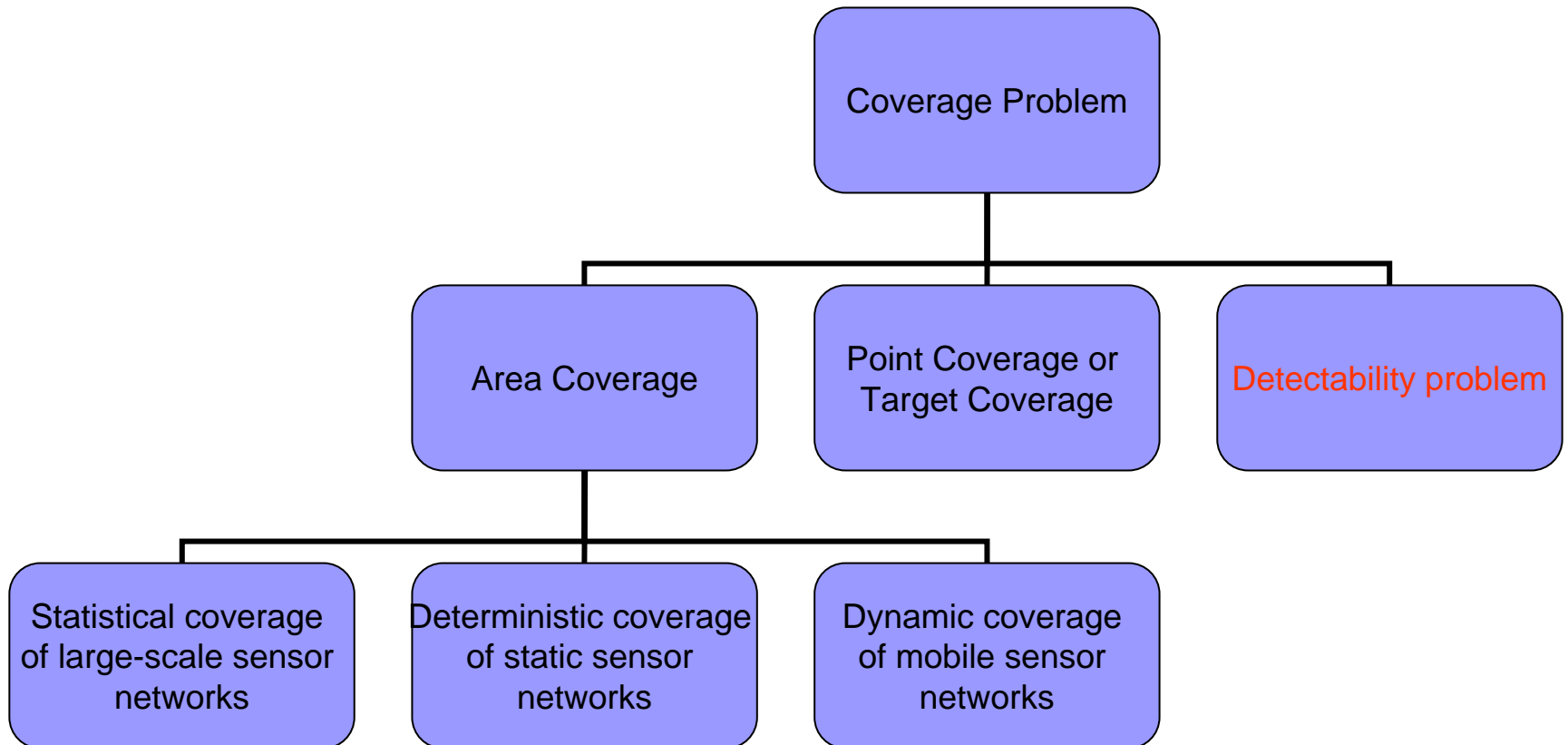
Fig. 2. Four cover sets: $S_1 = \{s_1, s_2\}$ for 0.5 time, $S_2 = \{s_2, s_3\}$ for 0.5 time, $S_3 = \{s_1, s_3\}$ for 0.5 time and $S_4 = \{s_4\}$ for 1 time

MSC is *NP*-complete[CT05]

[CT05] proposed two efficient heuristics, LP MSC and Greedy MSC heuristic, using a linear programming formulation and greedy approach, respectively.



Structure of my lecture presentation



Detectability problem

- A sensor network may need to detect intruders. An intruder may start at a point S , follow an arbitrary trajectory (path), and stop at some other point T .
- How to evaluate the vulnerability and efficiency of a sensor network?

Maximum breach path and maximum support path

- Given two points S and T , two relevant types of trajectories on the plane
 1. the maximum breach path: measures the vulnerability of sensor network. It is trajectory between the start point S and the stop point T that stays “as far away” from the sensors as possible.
 2. The maximum support path: measures the efficiency of the network coverage. It is trajectory between the start point S and the stop point T that stays “as close to the sensors” as possible

Formal definition

- A **maximum breach path** from **S** to **T** is a path such that the minimum distance from a point **P** in the path to the sensor network is maximized. And this distance is called the **worst-case coverage distance** of the network.
- A **maximum support path** from **S** to **T** is a path such that the maximum distance of a point **P** in the path to the sensor network is minimized. And the distance is called the **best-case coverage distance** of the network.

Related work

- [MK01] proposed optimal polynomial-time algorithms for searching the maximum breach path and maximum support path of a sensor network.
- [HW05] proposed an algorithm to maintain a $(1 + \varepsilon)$ approximation on the best case coverage distance and a $(\sqrt{2} + \varepsilon)$ approximation on the worst case coverage distance of the network, for a fixed $\varepsilon > 0$

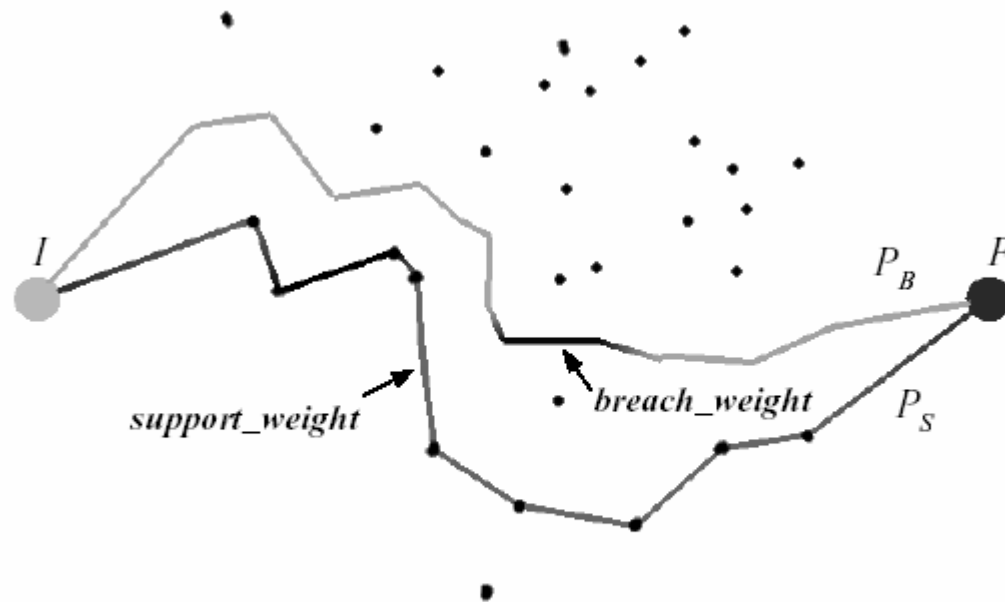


Figure 3 - Sensor Field with Maximal Breach Path (P_B) And Maximal Support Path (P_S)

Conclusion and future work

■ Conclusion

Many coverage problems in sensor network are *NP*-complete optimization problems, so now we only can propose some heuristic algorithms to solve them.

■ Future work

Developing coverage based on realistic assumptions, utilizing mobile sensors for achieving differentiated multiple coverage, finding some more efficient and resilient algorithm for these *NP*-complete problems are still under study.

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