Energy Efficient Area Monitoring Using Information Coverage in Wireless Sensor Network

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WOWMOM 2007

19th June , Helsinki

Outline

- Introduction
- Background
- Coverage
  - Physical Coverage Vs Information Coverage
- Proposed GB-FAIC Algorithm
- Result and Discussion

Introduction

- Wireless Sensor Networks
  - Energy efficiency is crucial in battery operated tiny sensors(nodes).
  - Energy is consumed primarily in **Sensing** (coverage of a point/target), Communicating and Processing of data.
  - Depletion of battery causes
    - End of Network lifetime

Background

- Coverage (sensing) - A point or target is said to be covered if a sensor node is able to sense it.
  - Physical Coverage (Classical sensing)
    - Sensing a target within a fixed radius(PCR) with acceptable accuracy.
    - Only one node takes part.
  - Information Coverage [a]
    - Sensing a target is feasible even beyond the fixed radius with acceptable accuracy.
    - Multiple nodes collaborate.

[a] B. Wang, W. Wang, V. Srinivasan, and K. C. Chua, "Information coverage for wireless sensor networks," IEEE Commun. Letters, vol. 9, no. 11, pp. 967-969, November 2005.

Information Coverage

- A collaborative strategy to enhance feasible sensing range beyond physical coverage region.
  - Useful for low node density sensor network.
- Improvement in Coverage at the cost of excess energy expenditure (Sensing a target involves more than one node).

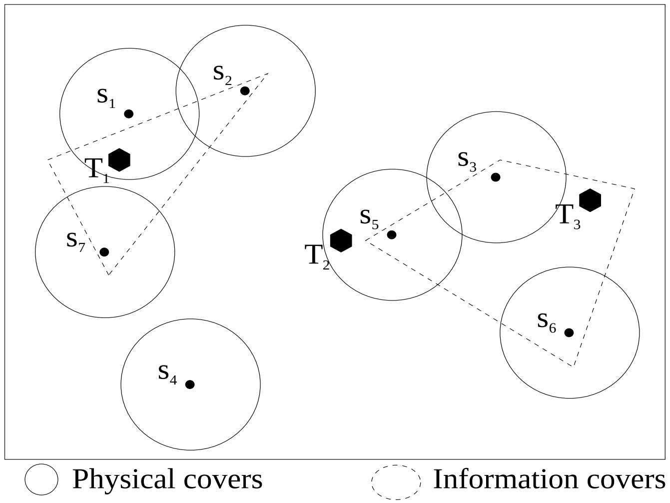

Figure 1: Target T_3 is out of Physical Coverage region

Information Coverage (Contd.)

- Measured value y_i ,

$$y_i = \frac{\theta}{d_i^{\alpha}} + n_i \text{ , i=1, 2, ...K(sensor node)}$$

  $\alpha =$ exponential decay component($\alpha > 0$)

  $\theta =$ parameter to be sensed/measured

  $d_i =$ distance between sensor node i and target

  $n_i =$ additive noise at sensor node i.

- Estimation error

$$\tilde{\theta} = \hat{\theta} - \theta$$

  $\hat{\theta}$= estimation of the parameter θ

- $\tilde{\theta}_K$ is the estimation error when K nodes collaborate

- A target is said to be (K, ϵ) information covered if K sensor collaborate to estimate the parameter θ at the target ,such that

$$\text{Pr}\{\mid \tilde{\theta}_K \mid \leq \text{A}\} \geq \varepsilon \text{ , where } 0 < \varepsilon < 1$$

Information Coverage -An Illustration

- Extension of coverage area (in black color) using information collaboration of 2 and 3 nodes

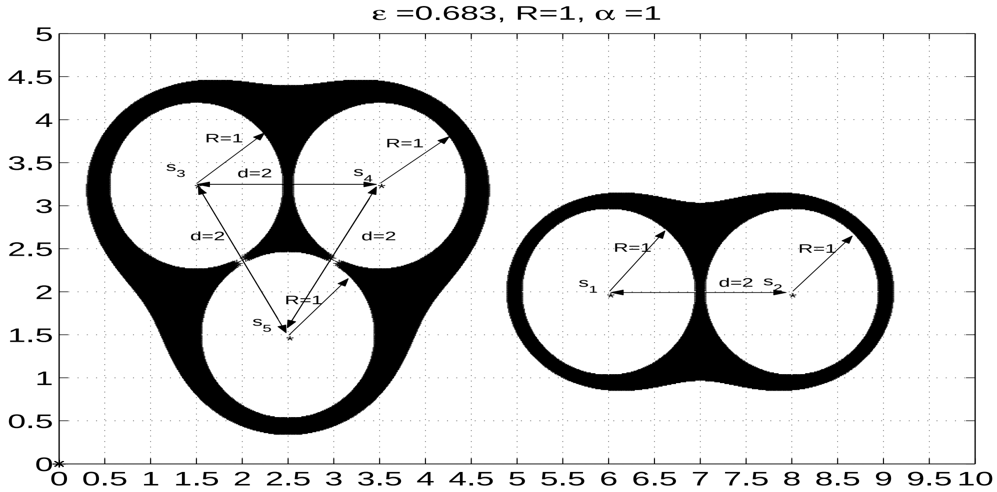

Figure 2: **Illustration of area covered by physical coverage and information coverage.**

Full Area Information Coverage

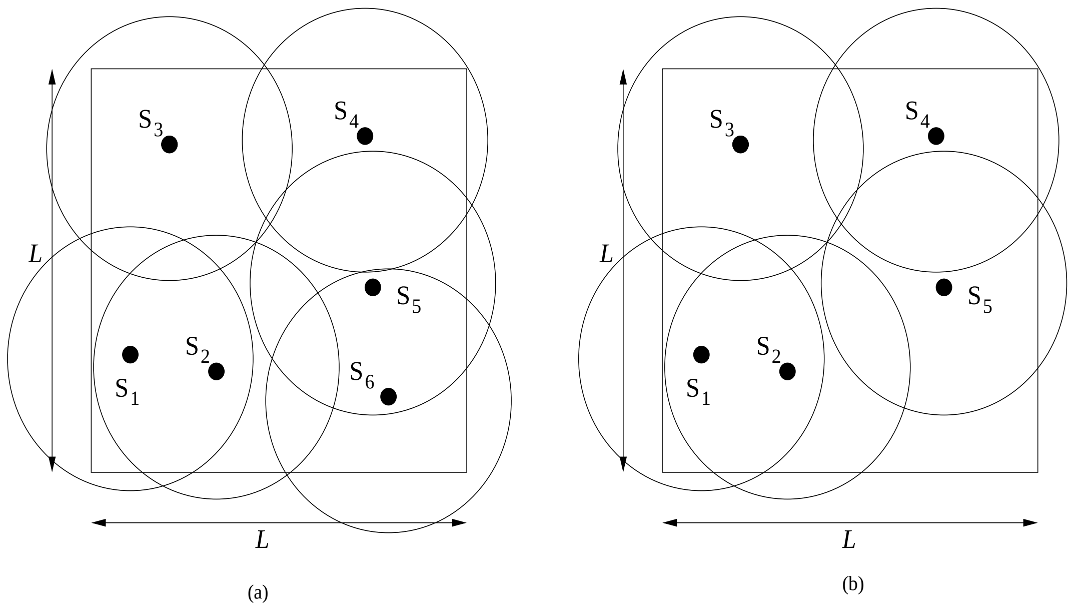

Figure 3: Illustration of full and partial area physical coverage. (a) Full area physical coverage by sensors $s_1, s_2, \cdots, s_6$. (b)Partial area physical coverage by sensors $s_1, s_2, \cdots, s_5$.

Full Area Information Coverage (Contd.)

- Ensuring sensing/monitoring of the full area-to-monitor essentially guarantees sensing/monitoring of any number of targets lying inside the area-to-monitor irrespective of their locations.
- The full area-to-monitor can be viewed as a collection of large number of densely populated point targets.

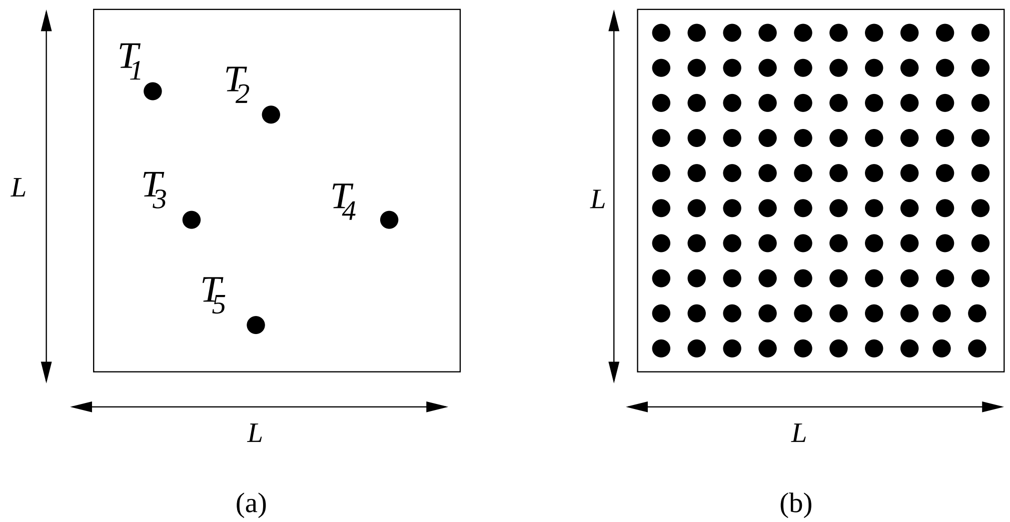

Figure 4: **(a) Point targets coverage problem. →(b) Full area coverage problem viewed as a point targets coverage problem.**

Point target coverage → Full area coverage

- Coverage
  - Point target Coverage
    - Objective is to cover one or more(few) point target by using information collaboration of multiple nodes.
  - Full Area Coverage
    - The whole sensor network area to be covered. Assume large number of densely populated targets depending on the PCR.
- Algorithms developed for point targets information coverage (e.g., EGEH and DSIC) can't be used to achieve full area information coverage.
  - Complexity in these algorithms for large number of targets in prohibitively high.
  - Complexity in the DSIC algorithm grows exponentially in the number of targets.
- Our Contribution
  - A two step scheme(first) for area coverage using information coverage.

Proposed GB-FAIC Algorithm

- Step I
  - We propose a low-complexity heuristic approach to achieve full area information covers(FAIC).
    - ∗ An exhaustive search for FAICs among all sensors is expensive. Search only through those sensor combinations that are more likely to be beneficial.
    - ∗ Search for valid FAICs only among those sensors which are separated adequately apart so that
      - · information coverage among them is more likely to be feasible
      - · closely located sensors are given less preference to be in the same FAIC (since information coverage through very closely located sensors can be less beneficial).
  - Step II
    - ∗ Optimally schedule these FAICs (by solving an integer linear program) so that the sensing lifetime is maximized.

System Model

- N homogeneous sensor nodes distributed uniformly in the sensing field of area L×L.
  - $\mathcal{S} = \{s_1, s_2, \cdots, s_N\}$
- $\mathcal{P} = \{p_1, p_2, \cdots, p_{|\mathcal{P}|}\}$ denote the set of all pixels that characterize the full area.
- $\mathcal{C}$: Set of information covers[a].
  - $\mathcal{C} = \left\{C_1, C_2, \cdots, C_{|\mathcal{C}|}\right\}$
- The jth FAIC C_j, $j = 1, 2, \cdots, |\mathcal{C}|$, denotes a subset of $\mathcal{S}$ such that *all* pixels in $\mathcal{P}$ are information covered by using *all* sensors in C_j

$$C_j \bigcap C_k \neq \phi \text{ for } j \neq k$$

- (X_i, Y_i): coordinates of the sensor s_i.
- $D\left((A, B), (C, D)\right)$: the distance between two points with coordinates (A, B) and (C, D).

[a] An information cover for a point target is defined as a set of sensors which collectively can sense that target accurately.

Proposed GB-FAIC Algorithm (Contd.)

- Partition the entire area-to-monitor into square grids of size $d \times d$ (Fig. 5) so that one sensor from each grid can be taken and checked if these sensors together form a valid FAIC.

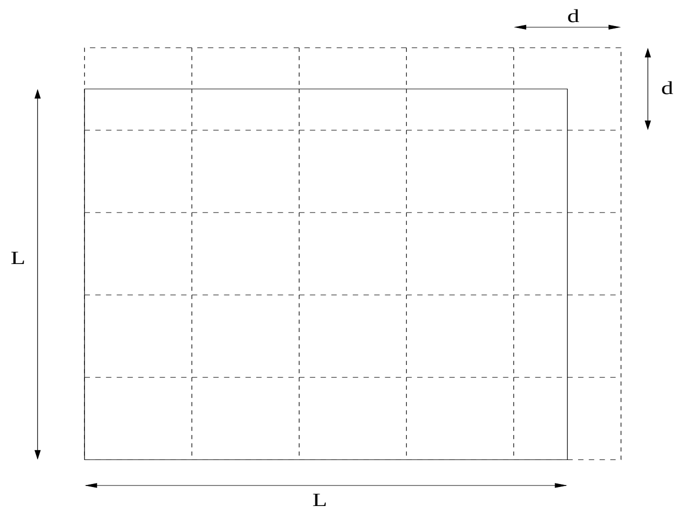

Figure 5: **Dividing the $L \times L$ area-to-monitor into square grids of size $d \times d$.**

Proposed GB-FAIC Algorithm (Contd.)

- Grid size ?.
  - Consider a square grid of size $d \times d$ with four sensors located at the four corners of the grid, as shown in Fig. 6.
  - Locate a point target at the center of the grid.
  - Find d_{max}(maximum value of d) for which all the four sensors together can sense the target.

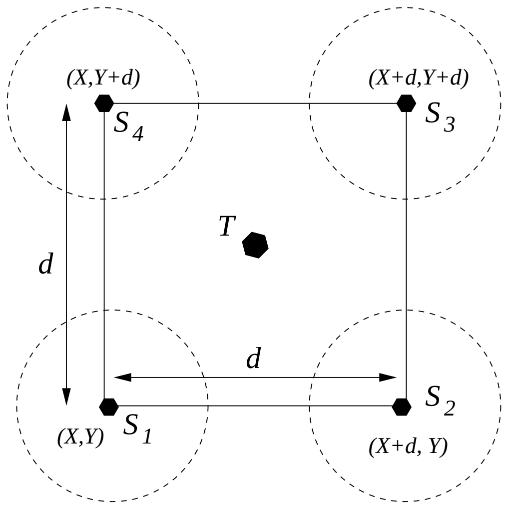

Figure 6: Choice of the grid size, d.

Proposed GB-FAIC Algorithm (Contd.)

- From the equation(Classical Information Coverage)

$$\Pr\{\mid \tilde{\theta_K} \mid \leq A\} \geq \varepsilon$$

- d_{max} can be calculated to be 2 for $\alpha = 2$ and $2\sqrt{2}$ for $\alpha = 1$.
- A grid size $\geq d_{max}$ will leave the target uncovered while grid size $\leq d_{max}$ will result in a larger search space without much coverage benefit.

Proposed GB-FAIC Algorithm (Contd.)

- The set of sensors for a valid FAIC test is chosen such that in each grid the sensor closest to its corner (if available) is chosen.
- The reference corner is alternatively taken to be the bottom left corner and top left corner (Fig. 7) to make the selected sensors in different sets to stay apart.

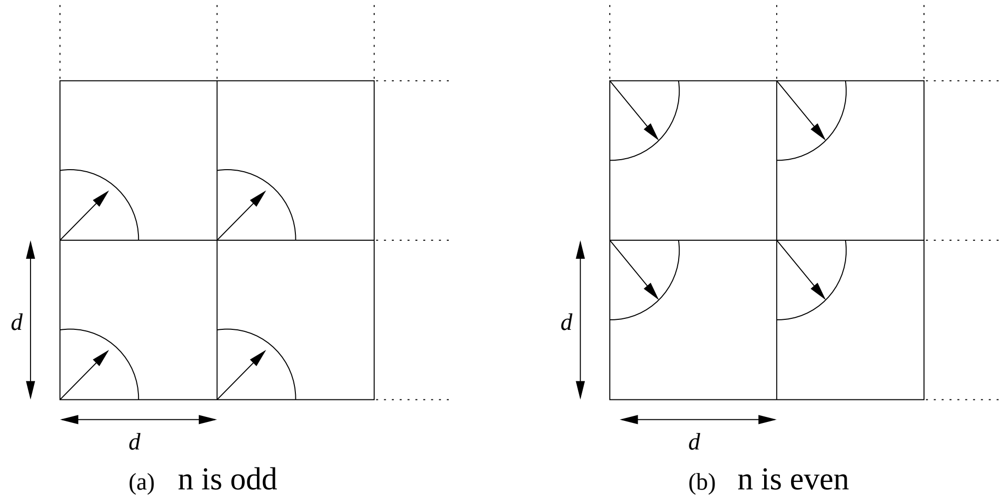

Figure 7: **Illustration of how sensors are selected in each grid.**

Proposed GB-FAIC Algorithm (Contd.)

$$C_j = \begin{cases} C_j \bigcup \big\{ s_i : \min \big[D\big((X_i, Y_i), (X, Y) \big) \big], \, i = 1, 2, \cdots, |\mathcal{S}_t| \big\}, \\ \qquad for \ j = odd, \ and \ (X \le X_i \le X + d, \ Y \le Y_i \le Y + d) \\ C_j \bigcup \big\{ s_i : \min \big[D\big((X_i, Y_i), (X, Y + d) \big) \big], \, i = 1, 2, \cdots, |\mathcal{S}_t| \big\} \\ \qquad for \ j = even, \ and \ (X \le X_i \le X + d, \ Y \le Y_i \le Y + d) \end{cases}$$

- $\mathcal{A}_{C_j}$ denotes the area (set of pixels) covered by the jth set of sensors through information coverage, such that

$$0 \le |\mathcal{A}_{C_j}| \le |\mathcal{P}| \quad (1)$$

and

$$\mathcal{A}_{C_j} \ge \mathcal{A}_{s_1} \bigcup \mathcal{A}_{s_2} \bigcup \cdots \mathcal{A}_{s_{|C_j|}}. \quad (2)$$

For physical coverage,

$$\mathcal{A}_{C_j} = \mathcal{A}_{s_1} \bigcup \mathcal{A}_{s_2} \bigcup \cdots \mathcal{A}_{s_{|C_j|}}. \quad (3)$$

Proposed GB-FAIC Algorithm (Contd.)

- If $\mathcal{A}_{C_j} \neq \mathcal{P}$.
  - $\mathcal{A}_{C_j}$: area covered by the set of sensors C_j.
  - $\mathcal{A}' = \mathcal{P} - \mathcal{A}_{C_j}$ (area not covered) by the set of sensors C_j.
- Algorithm attempts to cover the uncovered pixels $\mathcal{A}' = \mathcal{P} - \mathcal{A}_{C_j}$ by including additional sensors to the set C_j.

$$C_j = C_j \bigcup \{s_i : max[\mathcal{A}_{s_i} \in \mathcal{A}'],\ i = 1, 2, \cdots, N\} \tag{4}$$

- A valid set of FAICs is obtained as the output of the algorithm.
- The worst case complexity of the algorithm can be shown to be of order $|\mathcal{P}|N^3$.

Scheduling

- FAICs obtained from the proposed GB-FAIC algorithm are not disjoint.
- We consider that a cover is activated for an integer number of time slots.
- Scheduling algorithm is formulated as an integer linear programming (ILP) problem:
  - N_c: number of FAICs obtained from the GB-FAIC algorithm presented above.
  - T_j: activation time of the jth FAIC in number of time slots.
  - E_i: battery energy of sensor node i.

Scheduling (Contd.)

- The optimum schedule is obtained as the solution to the following optimization problem:

Maximize

$$\sum_{j=1}^{N_c} T_j \tag{5}$$

s.t

$$\sum_{j=1}^{N_c} C_{i,j} T_j \leq E_i, \quad \forall i = 1, 2 \cdots N, \tag{6}$$

where

$$C_{i,j} = \begin{cases} 1 & if \;\; s_i \in C_j \\ 0 & otherwise \end{cases}$$

and

$$T_j \in \{0, 1, 2, \cdots\}, \quad \forall j = 1, 2 \cdots, N_c. \tag{7}$$

Simulation parameter

- A network with 5×5 square sensing area.
- Initial battery energy of each sensor $E_0 = 2$ Joules(i.e. $E_i = 2$ Joules for $i = 1, 2 \cdots, N$).
- Each sensing operation when a sensor is activated to sense cost 4 nJ.
- No energy is consumed when the sensor is not activated (i.e., left idle).
- In each slot exactly one cover is activated for sensing operation.
- Sensing lifetime is the number of active time slots till full area coverage is maintained.
- Physical coverage range $R = 1$, α=1, and ϵ=0.683.
- Optimum schedules (i.e., T_j's) are obtained by solving the optimization problem in (5) using CPLEX 9.0.
- Assumptions
  - All sensor have fixed and equal physical coverage range.
  - Time axis is divided into contiguous intervals with equal duration.
  - Cover is invalid if any sensor of the cover is dead.

Simulation Results

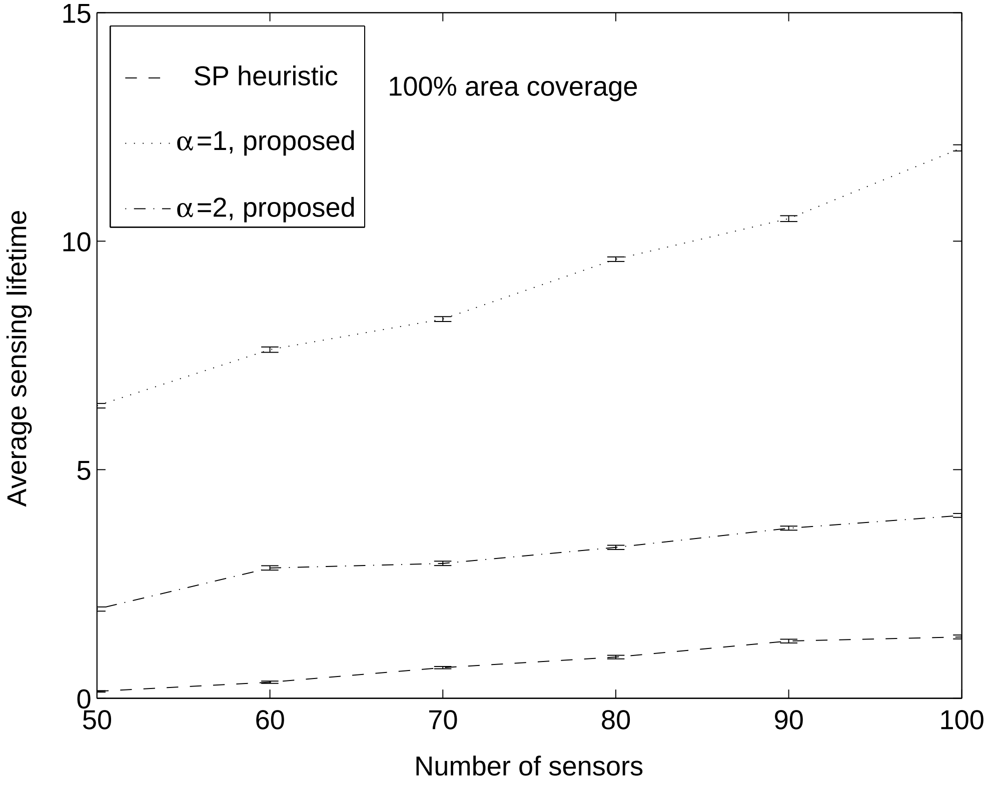

Figure 8: **Average sensing lifetime as a function of number of sensors in the network. Physical coverage (SP heuristic) vs information coverage (proposed). 100% area coverage.**

Simulation Results (Contd.)

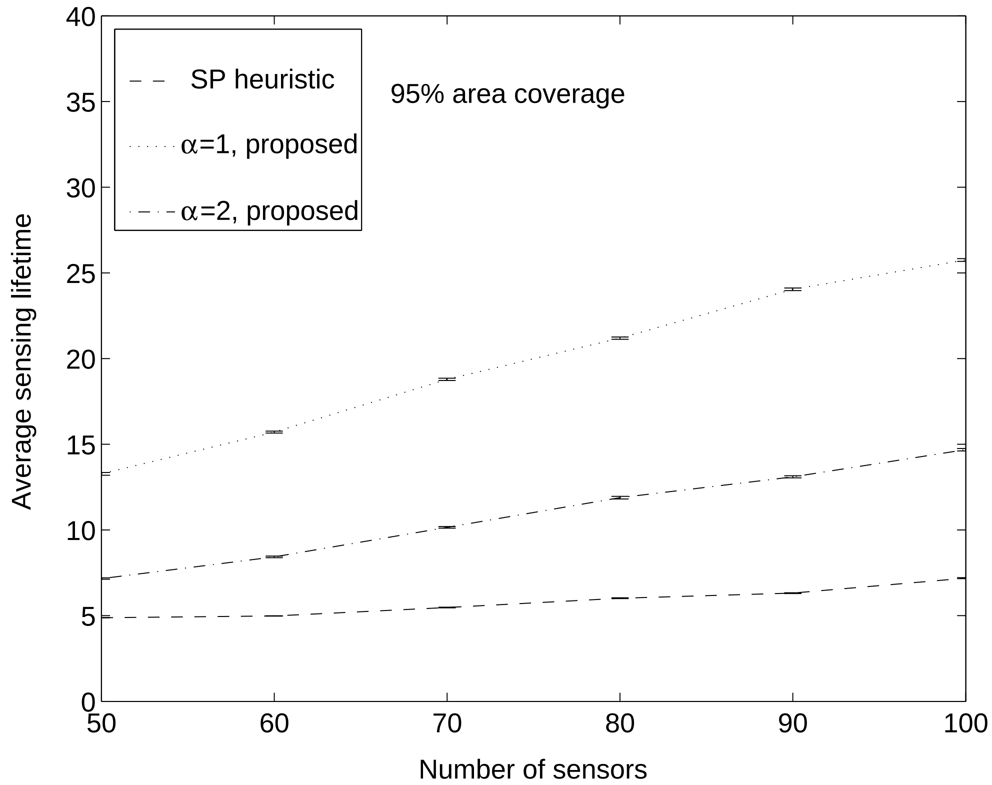

Figure 9: Average sensing lifetime as a function of number of sensors in the network. Physical coverage (SP heuristic) vs information coverage (proposed). 95% area coverage.

Simulation Results (Contd.)

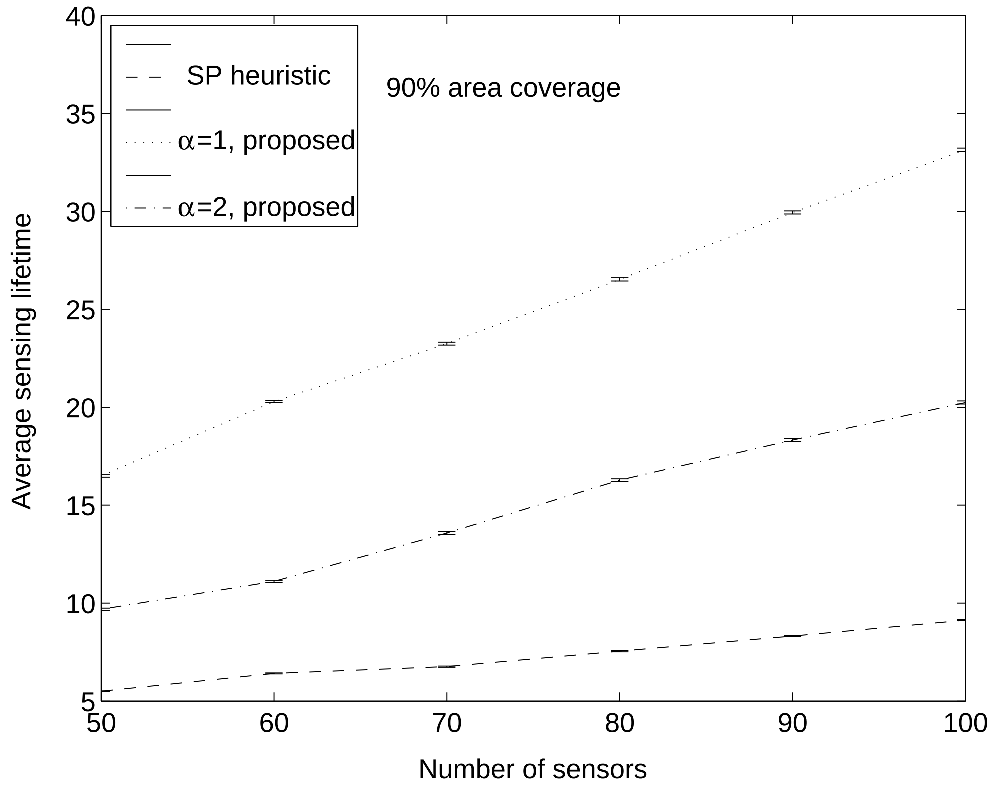

Figure 10: **Average sensing lifetime as a function of number of sensors in the network. Physical coverage (SP heuristic) vs information coverage (proposed). 90% area coverage.**

Conclusion

- Concept of information coverage is used to increase the network lifetime over physical coverage.
- We proposed GB-FAIC algorithm and compared the lifetime of network with physical coverage algorithm.
- Algorithm is proposed to cover the entire sensing field rather than point coverage.
- Simulation results shows the increase in sensing lifetime of network using information coverage.