Energy Efficient Area Monitoring Using Information Coverage in Wireless Sensor Networks*

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Abstract: In this paper, we are concerned with energy efficient area monitoring using *information coverage* in wireless sensor networks, where collaboration among multiple sensors can enable accurate sensing of a point in a given area-to-monitor even if that point falls outside the physical coverage of all the sensors. We refer to any set of sensors that can collectively sense all points in the entire area-to-monitor as a *full area information cover*. We first propose a low-complexity heuristic algorithm to obtain full area information covers. Using these covers, we then obtain the optimum schedule for activating the sensing activity of various sensors that maximizes the sensing lifetime. The scheduling of sensor activity using the optimum schedules obtained using the proposed algorithm is shown to achieve significantly longer sensing lifetimes compared to those achieved using physical coverage. Relaxing the full area coverage requirement to a partial area coverage (e.g., 95% of area coverage as adequate instead of 100% area coverage) further enhances the lifetime.

Keywords – *Information coverage, physical coverage, sensor scheduling, energy efficiency, sensing lifetime.*

1 Introduction

Recent advances in the area of embedded systems and wireless communications have enabled the development of small-sized, low-cost, low-power sensor nodes that can communicate over short distances wirelessly. In addition to their traditional sensing function, these sensor nodes can perform processing and communications functions. The processing and communication functions embedded in these sensor nodes essentially allow networking of these nodes, which in turn can facilitate sensing function to be carried out in remote/hostile areas. A network of sensor nodes (often referred to as a wireless sensor network) can be formed by deploying a large number of sensor nodes in a given sensing area, from where the sensed data from the various sensor nodes are transported to stations which are often located far away from the sensing area [1],[2]. Energy is consumed in the sensor nodes for the purpose of sensing as well as communication. Several studies in the literature have addressed the issue of minimizing the energy spent for the purpose of communication (e.g., energy efficient routing [3]). In this paper, we address the energy spent for the purpose of sensing, focusing on energy efficient algorithms for scheduling the sensing activity of sensor nodes *using Information Coverage* [4], instead of the often used physical coverage.

Sensor nodes in the network have the task of sensing/monitoring an area-to-sense/monitor and sending the sensed information to a sink. Not all nodes in the network may be needed to adequately cover (sense) the entire area-to-monitor. By intelligently switching the redundant sensor nodes to low power operation, the energy spent in sensing can be reduced, and hence the overall lifetime of the network can be increased. Redundant nodes can be deactivated as long as the area-to-monitor remains adequately covered by the other nodes, and activated when needed for adequate coverage.

The sensor coverage problem has been investigated by many in the literature [5]-[12]. In [5],[6],[7],[8], the authors address the problem of point target coverage (i.e., covering finite number of points in the sensing field). References [9],[10],[11],[12], on the other hand, addressed the problem of covering the entire area-to-monitor (instead of covering a few point targets as was done in [5]-[8]). In the above studies, each sensor node is assumed to have a well defined (usually circular) coverage region, i.e., a sensor node is considered to be able to accurately sense all points falling inside its coverage region, while it is considered to be unable to accurately sense points falling outside this coverage region. Radius of this circular region can be considered as physical coverage radius (PCR) of the sensor node. Given a set of sensor nodes deployed in an area to be sensed/monitored, the coverage problem then becomes a matter of determining whether every point in that area is in the PCR of at least one sensor.

More recently, Wang *et al*, in [4], have proposed a new coverage model, termed as *information coverage*, which is based on estimation theory to exploit collaboration among multiple sensors to accurately sense a point even if that point falls outside the PCR of all

*This work was supported in part by the Indo-French Centre for Promotion of Advanced Research, New Delhi, under Project 2900-IT.

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the sensors. That is, even if a point-to-be-sensed is not physically covered, it can be 'information covered' through multiple sensors collaborating to make an accurate estimation of the point. In [14], Wang *et al* studied the *point target coverage* problem using information coverage, and proposed a three-step heuristic referred to as Exhaustive-Greedy-Equalization Heuristic (EGEH) to obtain information covers[1] for scheduling the sensing activity of sensor nodes, allowing up to K_{max} sensor nodes to collaborate for achieving information coverage. Through simulations they showed that information coverage can result in longer sensing lifetimes compared to physical coverage. The information covers obtained using EGEH in [14] are not disjoint (i.e., a sensor can be present in multiple information covers). We, in [15], have proposed a two-step heuristic to obtain disjoint information covers for point target coverage, which we referred to as Disjoint Set Information Cover (DSIC) algorithm, and showed that our DSIC algorithm gave better sensing lifetimes compared to EGEH algorithm in [14] at the cost of higher complexity for large K_{max}. While [14] and [15] addressed the point target coverage problem using information coverage, to our knowledge, there has been no study reported so far on the *full area coverage* problem using information coverage.

Our new contribution in this paper is that we address the full area coverage problem using information coverage, which has not been reported before in the literature. We first propose a low-complexity heuristic algorithm to obtain *full area information covers* (FAIC), which we refer to as Grid Based FAIC (GB-FAIC) algorithm. Using these FAICs, we then obtain the optimum schedule for activating the sensing activity of various sensors that maximizes the sensing lifetime. Through simulation results, we show that the scheduling of sensor activity using the optimum schedules obtained using the proposed algorithm achieves significantly longer sensing lifetimes compared to those achieved using physical coverage. Also, as can be expected, relaxing the full area coverage requirement to a partial area coverage (e.g., 95% of area coverage as adequate instead of 100% area coverage) is shown to further enhance the sensing lifetime.

The rest of the paper is organized as follows. In Sec. 2, we present the preliminaries on information coverage. In Sec. 3, we present our work on point target coverage using information coverage. In Sec. 4.1, we present our work on full area coverage using information coverage, including the proposed GB-FAIC algorithm as well as the optimum scheduling algorithm. Simulation results and discussions are also presented. Conclusions are given in Sec. 6.

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

2 Information Coverage

In this section, we present the necessary preliminaries on the estimation theory based information coverage introduced in [4],[14]. Consider a sensing area with K spatially distributed sensor nodes s_i, $i = 1, 2, \cdots, K$. Consider a point target at a known location in the sensing area. Let θ be the physical quantity (or parameter) denoting the target that needs to be measured/monitored. Let d_i, $i = 1, 2, \cdots, K$ denote the distance between the target and sensor node s_i. Assume that θ varies inversely with distance (which is true with many physical quantities of interest, e.g., radiation level), with a decay exponent α, $\alpha > 0$, such that the parameter observed at distance d is given by $\theta d^{-\alpha}$. In addition to this decay, additive noise at the sensor also corrupts the observation at the sensor node. Accordingly, the observation of the parameter at sensor node s_i is given by

$$y_i = \theta d_i^{-\alpha} + n_i, \quad i = 1, 2, \cdots, K, \qquad (1)$$

where n_i denotes the additive noise at sensor node s_i. A linear unbiased estimator [13] can be employed to estimate θ using the K different observations, y_i's. Let $\hat{\theta}_K$ denote such an estimate of θ using K observations. This estimate will be more accurate for large K and small noise variances. Let $\tilde{\theta}_K$ denote the error in the estimation, given by

$$\tilde{\theta}_K = \theta - \hat{\theta}_K. \qquad (2)$$

For the estimate to be reliable, it is desired that the probability that the estimation error is less than a given value to be adequately large.

Definition: **(K, ϵ) Information coverage**
A target is said to be (K, ϵ) information covered, if K sensors collaborate to estimate the parameter θ at the target such that

$$\text{prob}\big(|\tilde{\theta}_K| \leq A\big) \geq \epsilon, \quad 0 \leq \epsilon \leq 1, \qquad (3)$$

where $\tilde{\theta}_K$ is the estimation error given by (2), and A is threshold level below which estimation error is acceptable.

Note-1: The special case of $(1, \epsilon)$ information coverage (i.e., $K = 1$) corresponds to physical coverage. It can also be seen that if a target is (K, ϵ) covered, then that target is also $(K+1, \epsilon)$ covered.

Illustration-1: Fig. 1 illustrates the physical and information covers in a rectangular sensing area with 3 targets $\{T_1, T_2, T_3\}$ and 7 sensors $\{s_1, s_2, \cdots, s_7\}$. It can be seen that target T_2 is physically covered by sensor s_5, and target T_1 is physically covered by sensor s_1. In addition, target T_1 is also $(2, \epsilon)$ information covered by sensors s_2 and s_7. Target T_3 is not physically covered, but it is $(3, \epsilon)$ information covered by sensors s_3, s_5 and s_6. Sensor s_4 contributes to

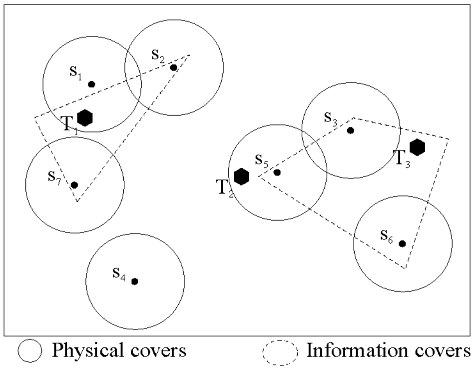


Figure 1: Illustration of physical covers and information covers for point targets.

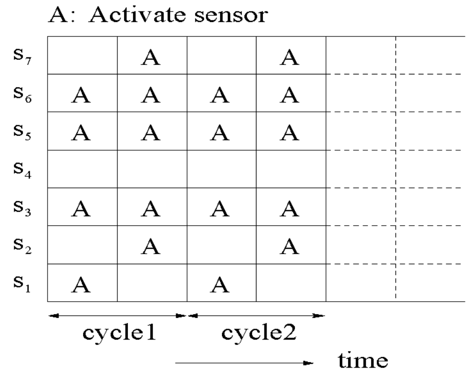


Figure 2: An illustration of scheduling the sensing activity of sensors using information covers in Fig. 1.

neither physical nor information coverage of any of the targets. In summary, *i)* $\{s_1, (s_2, s_7)\}$ is the set of feasible covers for target T_1, *ii)* $\{s_5\}$ is the set of feasible covers for target T_2, and *iii)* $\{(s_3, s_5, s_6)\}$ is the set of feasible covers for target T_3. Consequently, $\{(s_1, s_3, s_5, s_6), (s_2, s_7, s_3, s_5, s_6)\}$ is the set of feasible network information covers that can cover all the targets in this illustration.

Scheduling Sensing Activity using Covers: We note that the covers obtained are used to schedule the sensing activity of various sensors. In the illustration above, our aim is to cover all the targets in the network. Even if one target is not covered, then the network ceases to fulfill its sensing objective. In other words, sensing lifetime is the time up to which the deployed sensors can cover all the targets in the network. For example, in Fig. 1, if physical coverage is employed then target T_3 is not covered at all, and so the sensing lifetime in this case is zero (i.e., the network can never sense all targets using physical coverage). On the other hand, if information coverage is used as in the above illustration in Fig. 1, then the information covers (s_1, s_3, s_5, s_6) and $(s_2, s_7, s_3, s_5, s_6)$ can be alternatively scheduled to sense all the targets. That is, in time slot 1, sensors s_1, s_3, s_5, s_6 are activated, and in time slot 2, sensors s_2, s_3, s_5, s_6, s_7 are activated, and so on as shown in Fig. 2, such that this activation cycle is continued until both the information covers become invalid (a cover is said to become invalid if any of the sensors in that cover is fully drained out of its battery power, and because of which that cover can not sense all the targets). The problem we address in this paper is to obtain information covers that will result in long sensing lifetimes.

Area Covered by Information Coverage:

Note-2: An area is said to be completely (K, ϵ) covered if all the points in the area are (K, ϵ) covered.

Illustration-2: We present a comparison of the area covered by information coverage and physical coverage in Figs. 3 and 4. The physical coverage radius, R, is taken to be 1. This unit radius corresponds to a A value equal to the noise standard deviation σ, and an ϵ value equal to 0.683 for $(1, \epsilon)$ coverage (i.e., physical coverage) in Eqn. (3) [14]. The area covered by one sensor using physical coverage is then a circular area of unit radius, i.e., $\mathcal{A}_{(1,\epsilon=0.683)} = \pi R^2 = \pi = 3.14$. The area covered by two sensors s_1 and s_2, separated by distance $d = 2$ is shown in Fig. 3. While physical coverage in this case results in a covered area of $2\pi R^2 = 2\pi = 6.28$ (denoted by two circles each of radius R, centered at s_1 and s_2), the $(2, \epsilon)$ information coverage satisfying Eqn. (3) results in a larger covered area of 7.9 (area of two unit-radius circles plus the black shaded area around the two circles in Fig. 3). Similarly, the area covered by $(3, \epsilon)$ information coverage using sensors s_3, s_4, s_5 each separated from the other by $d = 2$ as shown in Fig. 3 is 12.9 whereas the area covered by physical coverage with these three sensors is only $3\pi = 9.42$. Figure 4 shows the area covered as a function of the sensor separation distance d in Fig. 3 both for physical coverage (PC) as well as information coverage (IC). From Fig. 4, it is observed that information coverage covers a larger area compared to physical coverage, $\mathcal{A}_{(K,\epsilon)} \geq \mathcal{A}_{(1,\epsilon)}$ for $K \geq 1$.

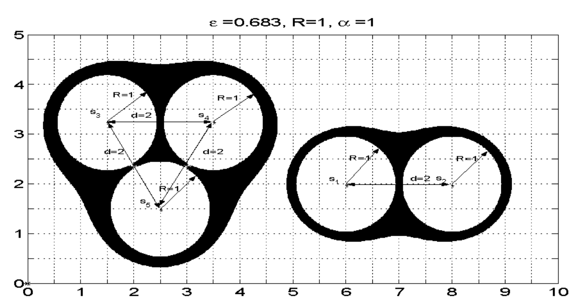


Figure 3: Illustration of area covered by physical coverage and information coverage.

3 Information Coverage for Point Targets

In [14], Wang *et al* proposed a Exhaustive-Greedy-Equalized Heuristic (EGEH) to obtain information covers for point targets. The information covers they

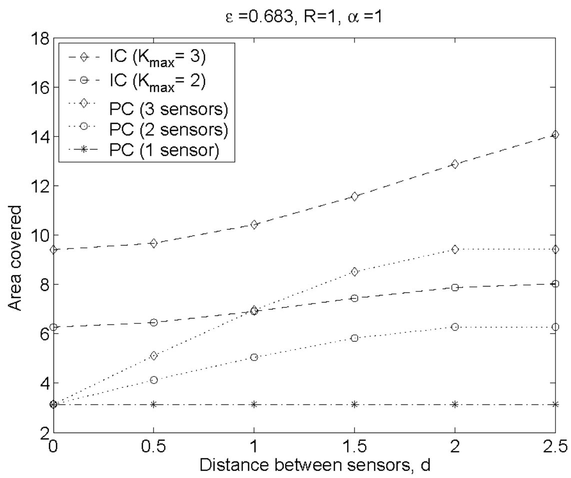


Figure 4: Area covered by physical coverage (PC) and information coverage (IC). $\alpha = 1$, $R = 1$, $\epsilon = 0.683$.

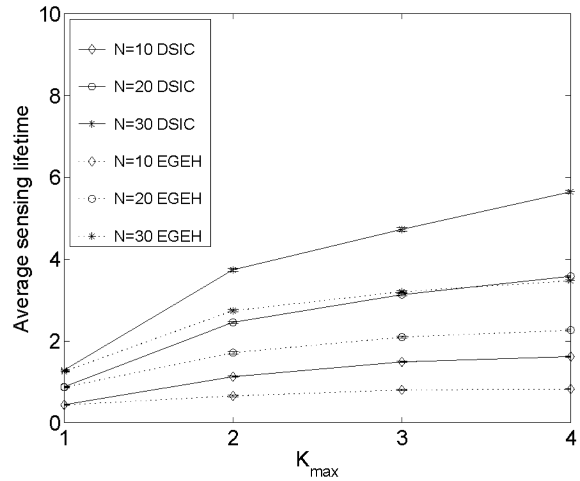


Figure 5: Average sensing lifetime versus K_{max} for $N = 10, 20, 30$, $M = 1$, $\alpha = 1$, $\epsilon = 0.683$, $R = 1$, initial battery energy = 2 J. DSIC versus EGEH.

obtained through EGEH are not disjoint. That is, a sensor can participate in more than one cover. Because of this, the resulting schedule of sensor activity is more involved than a simple round-robin schedule. Disjoint set covers, where a sensor can participate in at most one cover, on the other hand, are advantageous because a simple round-robin schedule is adequate.

The coverage problem using *disjoint set* of *physical* covers has been studied widely in the literature, where the disjoint set physical cover problem has been shown to be NP-complete [7], and so heuristics have been proposed to obtain disjoint set physical covers [7],[9],[18]. The problem of obtaining *disjoint set* of *information* covers is of interest. Accordingly, in [15], we addressed this problem of obtaining disjoint set of information covers for point targets, where we proposed a heuristic to obtain disjoint set information covers (DSIC). The proposed heuristic in [15], referred to as the DSIC algorithm, has been shown to achieve longer sensing lifetimes compared to the EGEH algorithm proposed in [14].

The operation of the DSIC algorithm in [15] is divided into two steps. In Step-I, disjoint set of information covers for each target in the network is obtained. In Step-II, using the outcome in Step-I, a disjoint set of information covers that can cover all the targets is obtained. Refer [15] for the detailed listing and description of the DSIC algorithm.

Performance of DSIC and EGEH Algorithms: We evaluated and compared the performance of the DSIC and EGEH algorithms through simulations. The following system model is considered in the simulations. A network with 5×5 square sensing area is considered. The number of sensor nodes in the network considered include $N = 10, 20, 30$. These sensor nodes are uniformly distributed in the sensing area. The number of targets in the network considered include $M = 1$ to 5. Each sensor is provided with an initial battery energy of 2 Joules. As in [16], we assume that each sensing operation when a sensor is activated to sense is $e_0 = 4\ nJ$. We also assume that no energy is consumed when the sensor is not activated (i.e., left idle). In all the simulations, we used the following parameters: $\alpha = 1$, physical coverage range $R = 1$, and $\epsilon = 0.683$. The maximum number of nodes allowed to collaborate is taken to be $K_{max} = 1, 2, 3, 4$.

In Fig. 5, we illustrate the average sensing lifetime as a function of K_{max} (the maximum number of sensors allowed to collaborate) obtained from the simulations by averaging over 100 different realizations of the network with 95% confidence inetrval. The performance of both DSIC as well as EGEH algorithms are shown for $N = 10, 20, 30$. It is observed that both the algorithms perform better than physical coverage (i.e., $K_{max} = 1$) – that is, due to information coverage, lifetime increases as K_{max} is increased. However, this improvement saturates for large values of K_{max} which can be expected (diminishing returns for increased K_{max}). It is also observed that the proposed DSIC algorithm performs better than the EGEH algorithm. The reason for this better performance can be attributed to the fact that EGEH returns covers which are not disjoint whereas as DSIC returns disjoint covers. Since a sensor can participate in more than one cover in EGEH, it can drain the battery power of those sensors participating in multiple covers sooner. This results in the network life to end soon (i.e., covers become invalid due to lack of battery power in sensors participating in multiple covers) even if some other sensors may have power left in their batteries. Whereas in the proposed DSIC, since the covers are disjoint, the energy in the sensors are fully used, resulting n longer sensing lifetime. Also, a simple round-robin scheduling is adequate for DSIC whereas a more elaborate scheduling is required for EGEH [14].

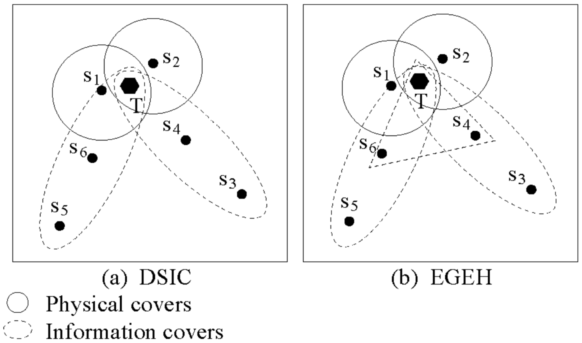


Figure 6: Illustration of information covers chosen by DSIC and EGEH.

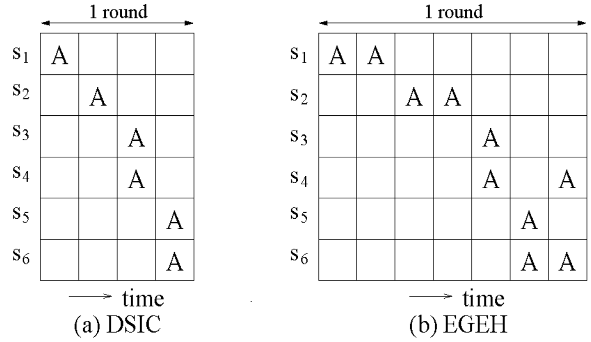


Figure 7: Illustration of scheduling of sensor activity in DSIC and EGEH.

We illustrate the above observations with an example using Figs. 6 and 7. Consider the network with nodes and a target as shown in Figs. 6 and 7. For this scenario, DSIC will return the following four information covers $\{s_1, s_2, (s_3, s_4), (s_5, s_6)\}$ (see Fig. 6(a)). Note that all the above covers are disjoint. Whereas EGEH will return the following five information covers $\{s_1, s_2, (s_3, s_4), (s_5, s_6), (s_4, s_6)\}$ (see Fig. 6(b)). Although EGEH 'greedily' returns more number of covers than DSIC, as can be seen, these covers are not disjoint (i.e., sensors s_4 and s_6 in EGEH are present in two covers). Further, the 'equalization' part in Step-3 of EGEH, in order to make the appearances (i.e., activation) of all sensors in the covers to be almost equal in a scheduling cycle, results in a more involved activity schedule as shown in Fig. 7(b). In the EGEH schedule in Fig. 7(b), sensors s_1 and s_2 are activated twice in a scheduling cycle in order to almost equalize the number of activations. Also, the sensing lifetime achieved in this EGEH schedule can be computed to be 3.5 (using the formulation in [14], which requires the LCM of certain weights of the covers which are proportional to the number of activations of the sensors in those covers). On the other hand, the covers returned by DSIC, being disjoint, results in a simple round-robin schedule as shown in Fig. 7(a) is adequate. In addition, the sensing lifetime achieved here is 4. Thus, by preferring to *i*) use disjoint covers, and *ii*) use far-away nodes (e.g., in Fig. 6(a), DSIC did not give preference to the nearby cover (s_4, s_6)), DSIC achieves better performance than EGEH. Fig. 3 illustrates the average sensing lifetime as a function of M, the number of targets in the network, for $N = 20, 30$ and $K_{max} = 4$. As the number of targets is increased, lifetime decreases, which is expected. Here again, DSIC is seen to achieve longer sensing lifetime than EGEH.

Complexity of DSIC and EGEH Algorithms: An approximate worst case analysis of the computational complexity of DSIC and EGEH algorithms has been carried out in [15], where the complexities of these two algorithms, respectively, are shown to be

$$H_{DSIC} \approx \left[2N^{K_{max}} M K_{max}^2 + N^{M+1}\right] \log N, \quad (4)$$

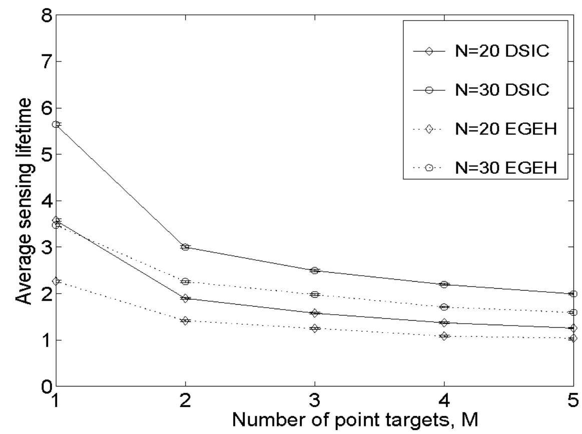


Figure 8: Average sensing lifetime versus number of point targets, M, to monitor. $N = 30, 20$, $K_{max} = 4$, $\alpha = 1$, $\epsilon = 0.683$, $R = 1$, initial battery energy $= 2$ J. DSIC versus EGEH.

and

$$H_{EGEH} \approx K_{max}(M + 2)N^{2K_{max}}. \quad (5)$$

From Eqns. (4) and (5), it can be seen that

- for $M + 1 > 2K_{max}$

$$\frac{H_{DSIC}}{H_{EGEH}} > 1,$$

- for $M + 1 < 2K_{max}$

$$\frac{H_{DSIC}}{H_{EGEH}} < 1,$$

- and for $M + 1 = 2K_{max}$

$$\frac{H_{DSIC}}{H_{EGEH}} \approx \frac{\log N}{K_{max}(M + 2)}.$$

From the above, it can be seen that the complexity of the DSIC algorithm can be less or more than the EGEH algorithm depending on the values of N, M, and K_{max}.

The observation made through an approximate worst case analysis in the above is also reflected in

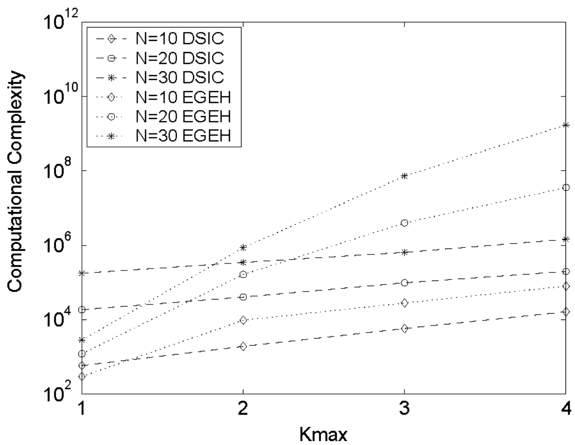


Figure 9: Computational complexity versus K_{max} obtained from simulations. $N = 10, 20, 30$, number of targets, $M = 4$. DSIC versus EGEH.

the complexity of the algorithms evaluated in the actual simulations. Fig. 9 shows the complexity of the algorithms as a function of K_{max} for 4 targets (i.e., $M = 4$) and $N = 10, 20, 30$, obtained from the simulations by averaging over 100 different network realizations. From this figure, it can be observed that the complexity of one algorithm is more or less than the other depending on the values of M (the number of targets), K_{max} (the maximum number of sensors allowed to collaborate), and N (the number of sensors). It is noted that the cross-overs between the resulting complexities of DSIC and EGEH algorithms seen in Fig. 9 essentially corroborate with a similar observation we made based on the approximate worst case complexity analysis.

4 Information Coverage for Full Area

In this section, we consider full area coverage instead of point target coverage. We say that the full area to be monitored is covered if all the points in the area can be sensed accurately.

Illustration 3: Figure 10(a) illustrates an example of full area physical coverage where all points in the $L \times L$ sensing area is covered by six sensors $s_1, s_2, s_3, s_4, s_5, s_6$. In Fig. 10(b), on the other hand, in the absence of sensor s_6, full area physical coverage is not achieved (some portion in the sensing area is not covered).

Illustration 4: Fig. 11 illustrates an example of full area information coverage by four sensors s_1, s_2, s_3, s_4. In addition to the PCR of these sensors (shown by the circles of radius R centered at the location of these sensors), all the points in the shaded region are also collaboratively covered by these sensors. Thus, in contrast to physical coverage, information coverage requires lesser number of sensors to cover the entire sensing area. Figure 12 shows partial area information coverage in the absence of the sensor s_4.

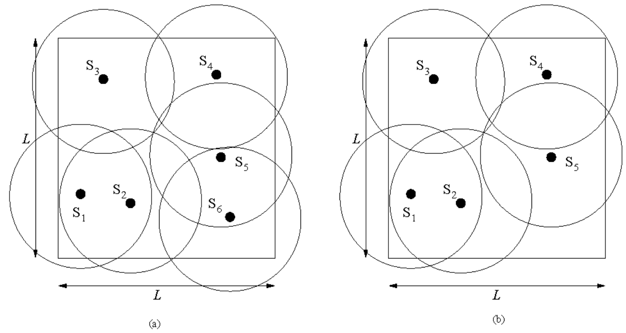


Figure 10: Illustration of full and partial area physical coverage. (a) Full area physical coverage by sensors $s_1, s_2, \cdots, s_6$. (b) Partial area physical coverage by sensors $s_1, s_2, \cdots, s_5$.

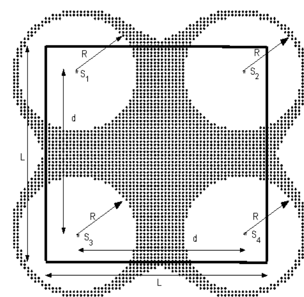


Figure 11: Illustration of full area information coverage by sensors s_1, s_2 $\cdots$

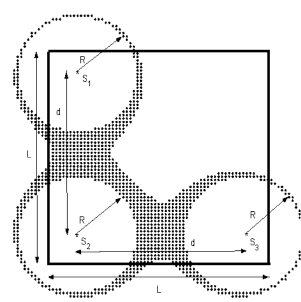


Figure 12: Illustration of partial area information coverage by sensors s_1, s_2, s_3.

4.1 Proposed Approach to Full Area Information Coverage

As pointed out in the previous section, a given point target can be sensed/monitored by one or more sensors using the information coverage approach. Here, we are interested in achieving full area information coverage. 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. Taking this view, algorithms developed for point targets information coverage (e.g., EGEH in [14] and DSIC in [15]) can be used to achieve full area information coverage. However, the complexity in these algorithms for large number of targets in prohibitively high. For example, the complexity in the DSIC algorithm grows exponentially in the number of targets [15]. Hence, we propose a low-complexity heuristic approach to achieve full area information coverage.

In the proposed approach, we first employ a low-complexity heuristic to obtain a set of full area information covers[2] (FAIC) by dividing the full area into finely spaced 'pixels' and treating these pixels as point targets[3] (Fig. 13). We then optimally schedule these FAICs (by solving an integer linear program) so that the sensing lifetime is maximized.

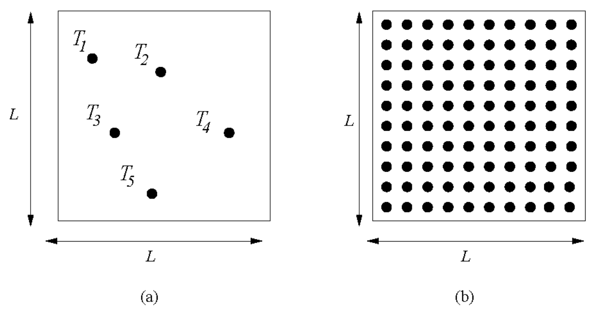


Figure 13: (a) Point targets coverage problem. (b) Full area coverage problem viewed as a point targets coverage problem.

System Model: Consider a set of N homogeneous sensor nodes $\mathcal{S} = \{s_1, s_2 \cdots, s_N\}$, which are distributed randomly in a square sensing field of area $L \times L$. Let the operator $|\mathcal{B}|$ denote the cardinality of set $\mathcal{B}$. Let $\mathcal{P} = \{p_1, p_2, \cdots, p_{|\mathcal{P}|}\}$ denote the set of all pixels that characterize the full area. Let

$$\mathcal{C} = \left\{C_1, C_2, \cdots, C_{|\mathcal{C}|}\right\}, \qquad (6)$$

$0 \leq |C_j| \leq N$, denote the set of full area information covers (FAIC). 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, and $C_j \bigcap C_k \neq \phi$ for $j \neq k$ (i.e., a sensor can take part in more than one FAIC). That is, FAICs are not necessarily disjoint.

4.2 Grid Based FAIC Algorithm

In this subsection, we present the proposed grid based algorithm for obtaining FAICs. An exhaustive search for FAICs among all sensors is expensive. Our idea is to avoid such a search through all possible sensor combinations, but search only through those sensor combinations that are more likely to be beneficial. The intuition behind the proposed heuristic is to search for valid FAICs only among those sensors which are separated adequately apart so that *a*) information coverage among them is more likely to be feasible, and *b*) 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).

In order to achieve the above objective, we partition the entire area-to-monitor into square grids of size $d \times d$ (Fig. 14) so that one sensor from each grid can be taken and checked if these sensors together form a valid FAIC. By adopting this approach, the search space for obtaining FAICs can get reduced depending on the choice of the grid size d. A large value of d is good from the complexity point-of-view but can be ineffective from the full coverage feasibility point-of-view (e.g., the extreme case of $d = L$ is most effective in terms of complexity and least effective in achieving full coverage). On the other hand, a small value of d can be very effective in achieving full coverage but it will not result in a significant reduction in the search space compared to an exhaustive search.

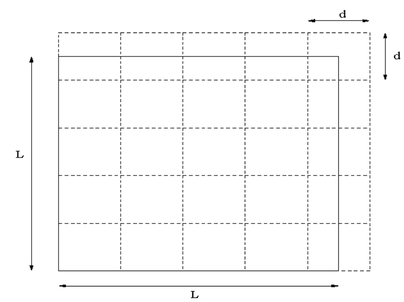


Figure 14: Dividing the $L \times L$ area-to-monitor into square grids of size $d \times d$.

Choice of the grid size, d: We propose to choose the grid size as follows. Consider a square grid of size $d \times d$ with four sensors located at the four corners of the grid, as shown in Fig. 15. Locate a point target at the center of the grid. Now, find the maximum value of d for which all the four sensors together can sense the target. We choose the grid size to be this maximum value. From the equations in Sec. 2, this maximum value can be calculated to be 2 for $\alpha = 2$ and $2\sqrt{2}$ for $\alpha = 1$. A grid size more than this maximum value will leave the target uncovered, whereas a grid size less than this maximum will result in a larger search space without much coverage benefit. So the proposed choice of grid size can result in a reasonable tradeoff between performance and complexity. The way the gridding is used in the algorithm is explained below.

Algorithm: The pseudo code for proposed algorithm is given in Table-I. In the algorithm, (X_i, Y_i) denotes the coordinates of the sensor s_i. $(X, Y), (X, Y + d), (X + d, Y), (X + d, Y + d)$ denote the coordinates of the four corners of a grid. $D\left((A, B), (C, D)\right)$ denotes the distance between two points with coordinates (A, B) and (C, D).

Lines 3 to 13: The set of sensors for a valid FAIC test is chosen such that in each grid the sensor closest to

[2] We define a full area information cover as any set of sensors that can collectively sense the entire area-to-monitor.

[3] In [9], such a slicing of area into 'pixels' is adopted for studying full area *physical coverage*.

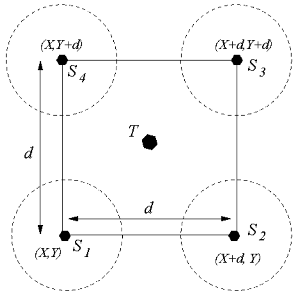


Figure 15: Choice of the grid size, d.

its corner (if available) is chosen. The reference corner is alternatively taken to be the bottom left corner and top left corner (Fig. 16) to make the selected sensors in different sets to stay apart. Lines 3 to 10 in the algorithm collects all possible sets of sensors for FAIC test based on the above criterion.

Line 16: For each of the sets of sensors obtained above, using the information coverage Eqns. in Sec. 2, the function $Area()$ obtains the set of pixels (i.e., area) that can be collaboratively sensed by these sensors. $\mathcal{A}_{C_j}$ denotes the area (set of pixels) covered by the jth set of sensors through information coverage, such that

$$0 \leq |\mathcal{A}_{C_j}| \leq |\mathcal{P}| \quad (7)$$

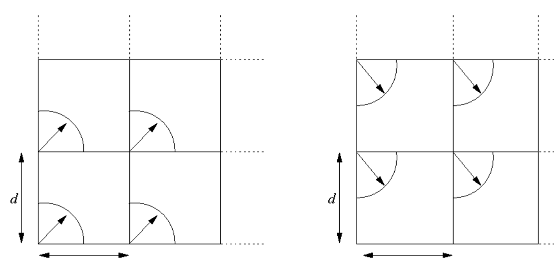
and

$$\mathcal{A}_{C_j} \geq \mathcal{A}_{s_1} \bigcup \mathcal{A}_{s_2} \bigcup \cdots \mathcal{A}_{s_{|C_j|}}. \quad (8)$$

Note that for physical coverage,

$$\mathcal{A}_{C_j} = \mathcal{A}_{s_1} \bigcup \mathcal{A}_{s_2} \bigcup \cdots \mathcal{A}_{s_{|C_j|}}. \quad (9)$$

Lines 17 to 25: It is possible that the jth set of sensors do not cover the whole area (all pixels), i.e., $\mathcal{A}_{C_j} \neq \mathcal{P}$). An illustration of $\mathcal{A}_{C_j}$ (area covered by jth set of sensors and $\mathcal{A}' = \mathcal{P} - \mathcal{A}_{C_j}$ (area not covered) is shown in Fig. 17. In that case, the algorithm attempts to cover the uncovered pixels $\mathcal{A}' = \mathcal{P} - \mathcal{A}_{C_j}$ by including additional sensors to the set as shown in line 19. This procedure is carried out on all sets of sensors resulting from lines 3 to 13, and 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 $|\mathcal{P}|N^3$.



(a) n is odd (b) n is even

Figure 16: Illustration of how sensors are selected in each grid.

Table-I: GB-FAIC Algorithm

1	$\mathcal{C} = \phi, n = 1, \mathcal{S}_t = \mathcal{S}$
2	**while** $(\lvert\mathcal{S}_t\rvert > 0)$
3	$X = Y = 0$
4	**while** $(X \leq L)$
5	**while** $(Y \leq L)$
6	$C_n = \begin{cases} C_n \cup \left\{s_i : \min\left[D\left((X_i,Y_i),(X,Y)\right)\right], i=1,2,\cdots,\lvert\mathcal{S}_t\rvert\right\}, \\ \quad for\ n=odd,\ and\ (X \leq X_i \leq X+d,\ Y \leq Y_i \leq Y+d) \\ C_n \cup \left\{s_i : \min\left[D\left((X_i,Y_i),(X,Y+d)\right)\right], i=1,2,\cdots,\lvert\mathcal{S}_t\rvert\right\} \\ \quad for\ n=even,\ and\ (X \leq X_i \leq X+d,\ Y \leq Y_i \leq Y+d) \end{cases}$
7	$\mathcal{S}_t = \mathcal{S}_t - \{s_i : s_i \in C_n\}$
8	$Y = Y + d$
9	**end while** Y
10	$X = X + d$
11	**end while** X
12	$n = n + 1$
13	**end while**
14	**loop** $j : 1 \leq j \leq n - 1$
15	$k = 1;$
16	$\mathcal{A}_{C_j} = Area(C_j)$
17	**while** $(\mathcal{A}_{C_j} \neq \mathcal{P})$
18	$\mathcal{A}' = \mathcal{P} - \mathcal{A}_{C_j}$
19	$C_j = C_j \bigcup \{s_i : max[\mathcal{A}_{s_i} \in \mathcal{A}'],\ i=1,2,\cdots,N\}$
20	$\mathcal{A}_{C_j} = Area(C_j)$
21	$k = k + 1;$
22	**if** $(k > N)$
23	$C_j = \phi$; **break**
24	**end if**
25	**end while**
26	**end loop** j

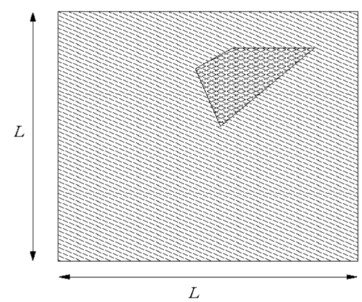


Figure 17: Illustration of areas information covered and not covered by a set of sensors. Single hashed area is covered area $\mathcal{A}_{C_j}$. Double hashed area is uncovered area $\mathcal{A}' = \mathcal{P} - \mathcal{A}_{C_j}$.

4.3 Optimum Scheduling of FAICs

Our aim is to cover *all* the pixels in the area-to-monitor. Even if one pixel is not covered, then the network ceases to fulfill its sensing objective. In other words, sensing lifetime is defined as the time up to which the deployed sensors can cover all the pixels in the area-to-monitor. FAICs obtained from the proposed GB-FAIC algorithm are not disjoint. These covers need to be scheduled optimally so that sensing lifetime is maximized. Considering that a cover is activated for an integer number of time slots, we formulate the scheduling algorithm as an integer linear programming (ILP) problem as follows. Let N_c denote the number of FAICs obtained from the GB-FAIC algorithm presented above. Let t_j denote the activation time of the jth FAIC in number of time slots. Let E_i denote the battery energy of sensor node i. The optimum schedule is obtained as the solution to the following optimization problem:

Maximize

$$\sum_{j=1}^{N_c} t_j \tag{10}$$

s.t

$$\sum_{j=1}^{N_c} C_{i,j} t_j \leq E_i/e_0, \quad \forall i = 1, 2 \cdots N, \tag{11}$$

where

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

and

$$t_j \in \{0, 1, 2, \cdots\}, \quad \forall j = 1, 2 \cdots, N_c. \tag{12}$$

5 Simulation Results

We evaluate the simulated performance of sensing lifetimes achieved by the proposed GB-FAIC and optimum scheduling algorithm, and compare it with the performance achieved using physical coverage.

Simulation model: A network with 5×5 square sensing area is considered. The number of sensor nodes in the network considered include $N = 50, 60, 70, 80, 90, 100$. These sensor nodes are uniformly distributed in the sensing area. Each sensor node is provided with an initial battery energy of 2 Joules. As before, we assume that each sensing operation when a sensor is activated to sense consumes $e_0 = 4\ nJ$. We also assume that no energy is consumed when the sensor is not activated (i.e., left idle). Time axis is divided into contiguous slots of equal duration. 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. In all the simulations, we used the following parameter values: α=1,2, physical coverage range $R = 1$ and the corresponding ϵ=0.683. Optimum schedules (i.e., t_j's) are obtained by solving the optimization problem in (10) using CPLEX 9.0.

Results: In Fig. 18, we illustrate the average sensing lifetime as a function of number of sensors for full area coverage, obtained from simulations by averaging over 100 different realizations of the network with 95% confidence interval. Lifeitmes achieved using the proposed GB-FAIC algorithm are plotted for $\alpha = 1$ and 2. The lifetimes achieved using the physical coverage based SP heuristic presented in [9] are also plotted for comparison. It can be seen that the proposed information coverage based algorithm results in significantly larger average sensing lifetimes compared to the physical coverage based SP heuristic in [9]. Figures 19 and 20 show the performance comparison between the proposed algorithm and the SP heuristic for 95% and 90% area coverage. Here again, the proposed algorithm performs better than the SP heuristic and a relaxed area coverage requirement (i.e., 90% coverage instead of full coverage) further increases the lifetime.

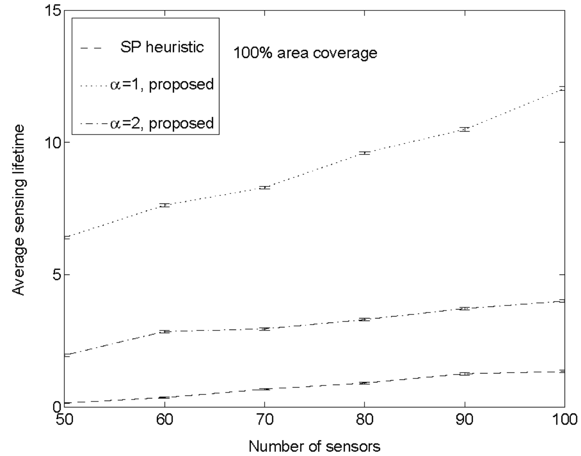


Figure 18: Average sensing lifetime as a function of number of sensors in the network. Physical coverage (SP heuristic) vs information coverage (proposed). 100% area coverage.

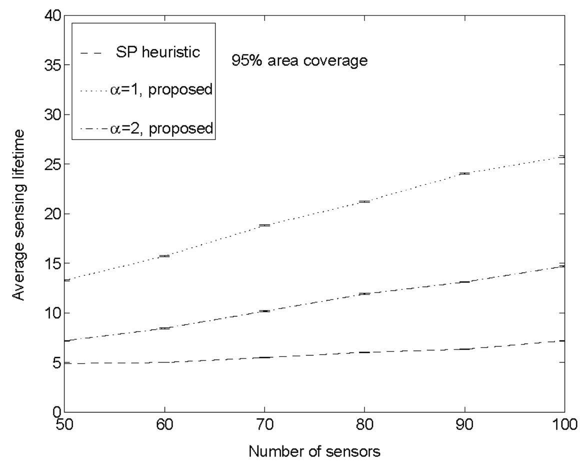


Figure 19: Average sensing lifetime as a function of number of sensors in the network. Physical coverage (SP heuristic) vs information coverage (proposed). 95% area coverage.

6 Conclusion

We investigated point target coverage problem and full area coverage problem in wireless sensor networks, adopting a novel information coverage model (instead of the widely adopted physical coverage model). The information coverage model essentially exploits the benefit of cooperation among sensors in order to achieve increased sensing lifetime of the network. For the point target coverage problem using information coverage, we presented a heuristic to obtain disjoint information covers that outperformed other known heuristics in the literature. For the full area coverage problem using information coverage, we proposed a low-complexity heuristic algorithm for obtaining full area information covers. Optimum schedules for activating various full area information covers were obtained by solving an ILP that maximized the sensing lifetime. The proposed approach was shown to result in significantly higher average sensing lifetimes compared to those obtained using physical coverage based sensing.

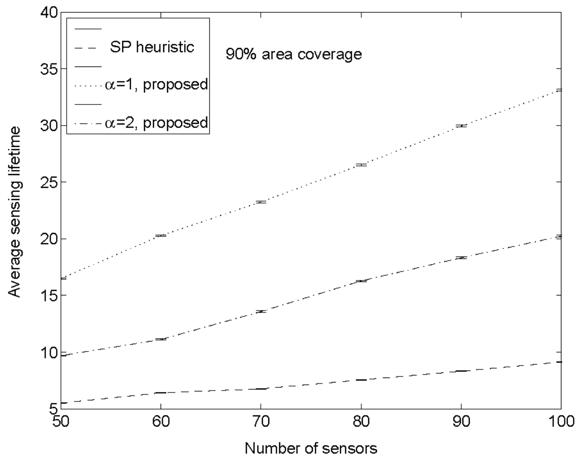


Figure 20: Average sensing lifetime as a function of number of sensors in the network. Physical coverage (SP heuristic) vs information coverage (proposed). 90% area coverage.

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