Maximum Lifetime of Sensor Networks with Adjustable Sensing Range

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Abstract

In this paper, we consider the problem of maximizing the lifetime of a target-covering sensor network in which each sensor can adjust its sensing range. The network model consists of a large number of sensors with adjustable sensing ranges being deployed to monitor a set of targets. Since more than one sensor can cover a target, in order to be energy efficient, one can activate successive subsets of sensors that cover all targets. This paper addresses the problem of maximizing the total lifetime of such an activation schedule.

In contrast to the approach taken by Cardei et al. [4], our formulation directly maximizes the network lifetime rather than maximizing the number of sensor covers. We give a mathematical model of this problem using a linear program with exponential number of variables and solve this linear program using the approximation algorithm of Garg-Könemann [8]. Our experimental results on simulated data show a 4x increase in lifetime when compared with the previous approach taken by Cardei et al. [4].

1. Introduction

Wireless sensor networks consist of a number of low-power low-cost sensors scattered randomly in a geographical area of interest and connected by a wireless RF interface. Sensors gather information about the monitored area and send this information to gateway node(s) [7]. The envisioned use of these networks is in military, disaster relief and rescue, healthcare settings etc.

Due to their low cost, these networks are dense, comprising of hundreds of sensors. However, a major constraint of these networks is energy. This is due to the fact that each sensor is equipped with a limited power supply in the form of a battery. Since these batteries cannot be recharged, we need to utilize the sensors in an efficient manner so as to increase the lifetime of the network. Another factor here has been the slow improvement in the battery capacities over the years as far as the chemistry is concerned [9]. Thus most energy savings need to come from energy aware protocols.

There are essentially two approaches to the problem of conserving power in sensor networks. The first consists of coming up with a schedule of active sensors that enables other sensors to go into a low power sleep mode. The second approach is that of adjusting the sensing range in order to meet application requirements. We deal with this in a similar manner to [4] by picking a set of active sensors as a number of set covers S_1, S_2, ..., S_m and assigning a lifetime to each cover t_1, t_2, …, t_m where t_i is the lifetime of set S_i.

In this paper, we consider the problem of maximizing the network lifetime for adjustable sensing range sensor networks. This problem was introduced by Cardei et al. [4] but our formulation differs significantly from theirs since we focus on maximizing the lifetime whereas they focus on maximizing the number of cover sets. Also, our problem formulation is more general as it can handle non-uniform batteries at the sensors as well as allow for a smooth sensing range variation as opposed to the discrete range model proposed in [4]. We give a provably good heuristic to find a monitoring schedule for sensor covers. Preliminary results indicate a four-fold improvement over existing approaches. This can be attributed to three factors: 1. A smoothly varying range model, 2. A provably good heuristic, and, 3. The ability to assign fractional time to each sensor cover.

The remainder of this paper is organized as follows. In Section 2, we review related work on the coverage problem. In Section 3, we provide the problem statement. Section 4 deals with a centralized solution to the problem and gives the linear program formulation. Section 5 defines the Minimum Weight Sensor Cover problem for adjustable range sensor networks and gives a greedy algorithm to solve it. In Section 6 we provide experimental results and, finally, Section 7 contains the conclusions and future work.

2. Related Work

Both the coverage and the lifetime problem have attracted considerable interest in recent years. Coverage problems for sensor networks have been classified into three broad groups – area coverage, target coverage and breach coverage [6].

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Various different scheduling schemes have been proposed in the literature which comprise of selection algorithms to pick subsets of sensors and a scheduling scheme that determines how long such a set is used [4, 5].

In [3] the authors introduce the target coverage problem and model it using disjoint set covers. They also prove the problem to be NP-complete and establish a lower bound of 2 on any polynomial time approximation.

It has been shown in [1, 2, 5] that non-disjoint sensor covers can provide better lifetime when compared to disjoint sensor covers and we use this result by generating non-disjoint covers.

[4] studies the problem of maximizing the lifetime of adjustable range sensor networks but our approach differs significantly from theirs as explained in Section 1.

Our work is an extension of the techniques used in [1, 2] where a similar problem was studied for fixed sensing range sensor networks.

3. Problem Statement

Sensor Network Lifetime Problem (SNLP) with range assignment: Given a monitored region R, a set of sensors $s_1, s_2, .. s_m$ and a set of targets $i_1, i_2, ... i_n$, and energy supply b_i for each sensor, find a monitoring schedule $(C_1,t_1), …, (C_k,t_k)$ *and* a range assignment for each sensor in a set C_i such that:

(1) $t_1+…+t_k$ is maximized,

(2) each set cover monitors all targets $i_1,…,i_n$ and,

(3) each sensor s_i does not appear in the sets $C_1,..C_k$ for a time more than b_i where bi is the initial energy of sensor s_i.

4. Centralized Maximization of Sensor Network Lifetime with Adjustable Sensing Range

4.1 Linear Program Formulation

In this section, we represent the SNLP with range assignment problem as a Linear Program problem and present a *(1+log n)* approximation for it.

The linear program corresponding to the problem presented in Section 3 can be stated as:

$$\textit{Maximize:} \sum_{j=1}^{m} t_j$$

$$\textit{Subject to} \sum_{j=1}^{m} C_{ij}\, t_j \le b_i \qquad (1)$$

where,

b_i is the battery for sensor *i,*

Rows i, i=1, …, n represent each sensor,

Columns j, j=1, …, m represent each sensor cover,

and, $C_{ij} = 0$ if sensor i is not in sensor cover j,

$C_{ij} = g(d)$, if sensor i is in sensor cover j with a sensing range fixed to d and g is a function of energy over distance.

Note that this LP formulation provided by us is substantially different from the one proposed by [4]. Their objective function maximizes the number of sensor covers up to some limit k, whereas we maximize the actual network lifetime t. Also, it can be shown that having more than n covers C_j with non-zero t_j is of no use, where n is the order of sensors. Thus, if the goal is to maximize the network lifetime, then the objective function of the LP should reflect this. Also, our LP allows for sensors to have non-uniform battery life.

The linear program (1) is a packing LP that can be represented by the general form,

$$max\{c^T x \mid Ax \le b, x \ge 0\} \qquad [8]$$

where, A, b and c are (m x n), (m x 1) and (n x 1) matrices whose entries are positive.

For the problem described above, the number of columns of the matrix A is exponential in the number of sensors and in order to overcome this, we use the Garg-Könemann algorithm [8] with an approximation ratio (1+ϵ). The algorithm assumes that the LP is implicitly given by a vector $b \in R^m$ and an algorithm that provides an f-approximation to find the column of A of minimizing length, where $length_y(j)= \sum_i A(i,j)\, y(i) / c(j)$ for any positive vector y. The algorithm is presented in Figure 1.

Input: A vector $b \in R^m$, $\varepsilon > 0$, and an f-approximation algorithm F for the problem of finding the minimum length column $A_{q(y)}$ of a packing LP $\{\max\ c^T x | Ax \le b, x \ge 0\}$

Output: A set of columns $\{A^j\}_{j=1}^{k}$ each supplied with the value of the corresponding variable x^j, such that $(x^1,\dots,x^k)$ correspond to all non-zero variables in a near-optimal feasible solution of the packing LP $\{\max\ c^T x | Ax \le b, x \ge 0\}$

(1) Initialize: $\delta = (1+\varepsilon)((1+\varepsilon)m)^{-1/\varepsilon}$, for $i = 1,\dots,m$ $y(i) \leftarrow \frac{\delta}{b(i)}$, $D \leftarrow m\delta$, $j = 0$

(2) While $D < 1$

Find the column A_q using the f-approximation F.

Compute p, the index of the row with the minimum $\frac{b(i)}{A_q(i)}$

$j \leftarrow j+1$, $x^j \leftarrow \frac{b(p)}{A_q(p)}$, $A^j \leftarrow A_q$

For $i = 1,\dots,m$, $y(i) \leftarrow y(i)\left(1+\varepsilon \frac{b(p)}{A_q(p)} / \frac{b(i)}{A_q(i)}\right)$, $D \leftarrow b^T y$.

(3) Output $\{(A^j, \frac{x^j}{\log_{1+\varepsilon} \frac{1+\varepsilon}{\delta}})\}_{j=1}^{k}$

Fig 1. The Garg-Könemann Algorithm [1]

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1. For each sensor s_i compute the vector D_i given below $D_i = [\, 1/e_{i1}, \ldots, m/e_{im}]$ Here, the numerator represents number of targets covered, and, m is the number of targets it can cover with range set to MAXDIST
2. Find the maximum value of D_i
3. Divide D_i / *weight* *weight* is the variable from Garg-Könemann for the next step
4. Insert D_i /*weight* into a heap, along with (m_i, r_p) which represents number of uncovered targets and the sensing range respectively.
5. Extract P=max(m_i*, r_p*) from the Binary Heap

6. Update Binary Heap
for each target t_j covered by P
for each sensor i in the Binary Heap
for each $\alpha \in D_i$ vector of that sensor
if ($d_\alpha \geq d_{ij}$) then
$M_\alpha = M_\alpha - 1$
//reduce uncovered targets
else
break

7. Update max, rebuild Heap
8. Repeat 2-7 until all targets are covered

Fig 2. The Greedy Algorithm for the Minimum Weight Sensor Cover Problem with Adjustable Sensing Ranges

This is a similar approach as taken by [1], [2] in solving the fixed range maximum lifetime problem. What changes here is our *f*-approximation algorithm which now assigns ranges to every sensor and factors in the increase in energy consumption due to the increase in distance while choosing a sensor cover. This is explained in more detail in the following section.

THEOREM 4.1. *The Lifetime problem with adjustable sensing range assignment can be approximated within a factor of (1+є) f, for any* є > 0 *by using the Algorithm of Fig. 1, where f is the approximation ratio of the algorithm that picks the minimum weight column in Fig. 1.*

This result is implied by the Garg-Könemann algorithm [8].

5. Minimum Weight Sensor Cover with Adjustable Sensing Range

Minimum Weight Sensor Cover Problem with Adjustable Sensing Range. Given a monitored region R, a set of sensors $s_1, s_2, \ldots, s_n$ and a set of targets covered by each sensor for a range r_i and the weight w_i for each sensor, find the sensor cover with minimum total weight.

With an adjustable sensing range sensor network, the problem of generating covers becomes much more interesting since we can now generate more covers simply by varying the range of a sensor. In order to cover more targets we can increase the sensing range but this comes at the cost of increasing the energy consumed. So the question really is one of what is the best sensing range a sensor can pick to cover uncovered targets while taking into account increases in energy with distance.

Our *f*-approximation is a greedy heuristic that tries to add sensors to the set cover by picking a sensor s_i with a sensing range r_i that maximizes the following ratio:

$$Gval(s_i) = \frac{\text{No. of uncovered targets covered by } s_i}{\text{weight x } e_i}$$

Here, weight is the packing LP variable and is updated by Garg-Könemann. Also, e_i is a function of the distance d_{ij} between sensor s_i and target t_j and can be varied to study linear, quadratic and other energy models.

The algorithm is outlined in Fig. 2. We assume that there exists a cutoff distance *MAXDIST* beyond which no sensor can increase its distance.

THEOREM 5.1. *The Greedy Algorithm for the Minimum Weight Sensor Cover Problem with Adjustable Sensing Ranges has an approximation ratio (1+ln k).*

This is from the standard greedy algorithm for the Minimum Weight Set Cover Problem with *k* points to cover.

COROLLARY 5.2. *The Lifetime problem with adjustable sensing range assignment can be approximated within a factor of (1+є) (1+ln m) for any* є > 0 *by using the Algorithm of Fig. 1.*

This result comes from Theorem 4.1 and Theorem 5.1 with *k=O(m)* elements to cover, *m* being the number of targets.

6. Experimental Results

In this section, we evaluate the performance of our heuristic and compare it to that proposed in [4].

For simulation purposes we use a static network of sensors scattered in a 100m x 100m area. The adjustable parameters are:

- N the number of sensor nodes. We vary this from 80 to 200
- M the number of targets. Initial results are for 25 targets and 50 targets.
- The sensing range *r* which can vary smoothly from 5m to 60m

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In order to compare our results with [4], we use the linear and quadratic energy models defined by them. The linear model specifies the energy e_p needed to cover a target at distance r_p as $e_p=c_1*r_p$ where, c_1 is a constant. For the quadratic model, $e_p=c_2*r_p^2$ where, c_2 is a constant. The range variation is the same as that for the discrete model except for that fact that we allow it to vary smoothly. For comparison we run simulations against their distributed version.

We have implemented our algorithm in C++ and run experiments on randomly generated test cases. The ϵ value for the quality of the Garg- Könemann algorithm is set to 0.1. After finding sensor covers from Garg-Könemann we find the optimal schedule by assigning the best times for each cover by using CPLEX. Our results are shown in *Figure 3, 4 and 5*.

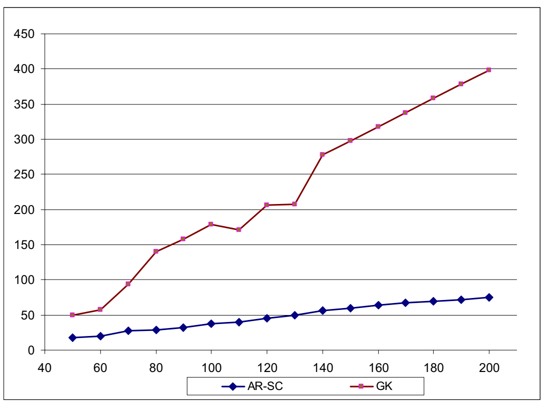

Fig 3. Variation in Network Lifetime with Number of Sensors. Number of Targets=25, Energy model is linear. AR-SC denotes the algorithm in [4]

Figure 3 and *Figure 4* illustrate the case with 25 and 50 targets respectively with a linear energy model. We measure the variation in Network Lifetime with an increase in the number of sensors. *Figure 5* repeats the same experiment with 25 targets and a quadratic energy model. As can be seen from the graphs, we have about an order of 4 times improvement in network lifetime.

The drastic performance improvement can be explained by the following reasons:

1. *Smoothly varying sensing range* - The adjustable range model used in [4] required that the sensing range be increased in '*P'* discrete steps. We allow a smooth variation up to a cutoff distance *MAXDIST*. This has the advantage that the sensor spends only the energy required to reach the target and no more. This is illustrated in Fig. 6, where the discrete scheme has to increase its range to r2 when the target is much closer at a distance r1.

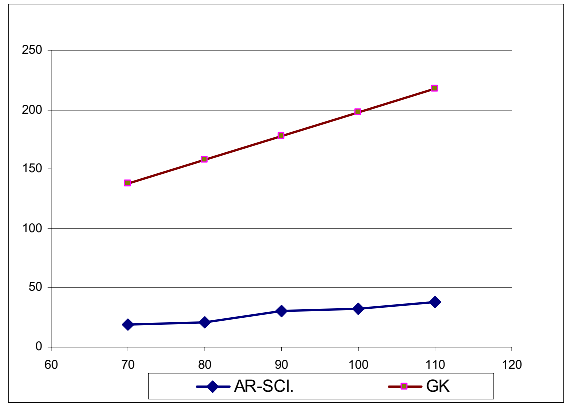

Fig 4. Variation in Network Lifetime with Number of Sensors. Number of Targets=50, Energy model is linear.

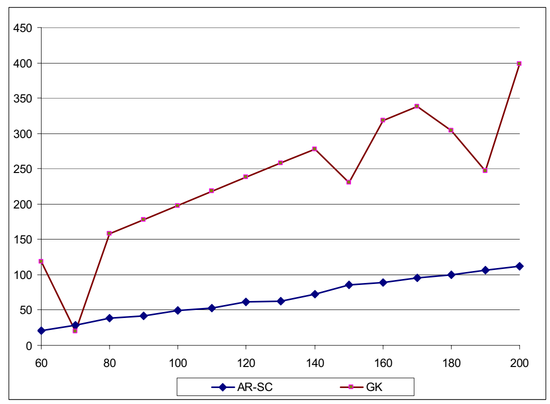

Fig 5. Variation in Network Lifetime with Number of Sensors. Number of Targets=25, Energy model is quadratic.

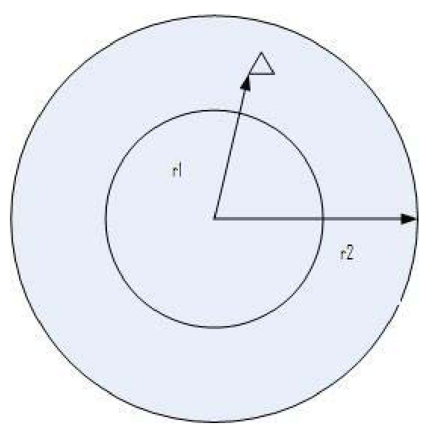

Fig 6. Discrete range assignment Vs. Smoothly varying range assignment.

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2. *Fractional time assignment to each sensor cover* - Due to our LP formulation, we can exploit the ability to assign fractional times to each sensor cover instead of assigning time in fixed intervals.

3. *Provably good algorithm* – As shown in Section 5 the heuristic has a provably good approximation ratio of (1+ln m).

7. Conclusions and Future Work

In this paper, we provided an alternative problem formulation for the lifetime maximization problem in a sensor network with adjustable sensing ranges. We present a packing LP formulation of the problem and give a provably good heuristic solution. Preliminary results indicate a significant improvement over existing approaches.

We are currently working on more extensive simulation results that consider different energy models and target numbers. Also, studying a distributed version of the above problem would be part of future work.

8. Acknowledgments

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