A Localized Algorithm for Target Monitoring in Wireless Sensor Networks

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Abstract. We consider the following target monitoring problem: Given a set of stationary targets $T = \{t_1, \cdots, t_m\}$ and a set $V = \{v_1, \cdots, v_n\}$ of sensors, the target monitoring problem asks for generating a family of subsets of sensors $V_1, \cdots, V_s$ called the *monitoring sets*, such that each V_i monitors all targets. In doing so, the objective of this problem is to maximize $z = s/k$, where $k = \max_{v_j \in V} |\{i : v_j \in V_i\}|$. Maximizing z has direct impact in prolonging the lifetime of sensor networks. For this problem, we present a simple *localized* algorithm which requires each node to know only its 2-hop neighborhood. Nodes do not need to know their geographic positions. It is shown that the algorithm achieves an optimum result in special cases. We prove that the size of a monitoring set is at most a constant times the size of a minimum monitoring set when the number of targets is a constant. We present extensive simulation results to evaluate the performance of the algorithm.

1 Introduction

In this paper, we study the *target monitoring problem*. Given a set of stationary targets $T = \{t_1, \cdots, t_m\}$ and a set $V = \{v_1, \cdots, v_n\}$ of sensors, the target monitoring problem asks for generating a set of subsets of sensors $V_1, V_2, \cdots, V_s$ called the *monitoring sets* such that each V_i monitors all targets. The idea is that only one such set is *active* (only active sensors monitor the targets) for any certain period of time and after that time period another set becomes active and so on, thus providing continuous monitoring. The objective of this problem is to maximize $z = s/k$, where $k = \max_{u \in V} |\{i : u \in V_i\}|$. Considering each i $(1 \leq i \leq s)$ as a round, we activate the sensors in V_i in round i to monitor all targets, while keeping $V \setminus V_i$ in the energy-efficient *sleep* mode. We use 'sensor' and 'node' interchangeably in what follows. We define an algorithm as p-localized if each node u is allowed to exchange messages with its neighbors which are at most $p-$hops away and take decisions accordingly based on this information. To solve the target monitoring problem, we propose a 2-localized algorithm. Furthermore, the nodes do not need to know their geographic positions. They only need to know the ids and the connectivity information of their 2-hop neighborhood.

The rest of the paper is organized as follows. In Section 2 we describe related work. In Section 3 we provide definitions and assumptions that are used throughout the paper. The localized algorithm is presented in Section 4 and a theoretical analysis of the algorithm follows in Section 5. Experimental results are presented in Section 6. We conclude in Section 7.

2 Related Work

Coverage (also called *monitoring*) has been one of the important topics in sensor networks and has received a lot of attention during the past several years [2–7]. The main goal of almost all the research on average is to devise scheduling algorithms such that individual sensors in the network are assigned *rounds* which indicate to them during which rounds they will be active and during which rounds they will be in the sleep mode. When a set of sensors monitors a certain area or a target, it is generally possible to monitor the area or the target by a *small* subset of them. So, it is redundant to make all the sensors active at the same for the monitoring instead of using the small subset. This observation leads researchers to devise efficient algorithms such that at any time only a few sensors are set as active to monitor the area or the targets. A recent result related to our problem is described in [1], where the authors consider the *monitoring schedule* problem: Given a set of sensors and a set of targets it is required to find a partition of the sensor set such that each part can monitor all targets. Each part of the partition is used for one unit of time and the goal is to maximize the number of parts in the partition. They present a randomized distributed algorithm which generates at least $(1 - \epsilon) * opt$ parts, with high probability, where opt is the maximum number of parts in the partition and $0 < \epsilon < 1$. However, they make the assumption that the sensors must know their geographic positions. The authors also show that by modifying their algorithm they can find a constant approximation factor for the problem and the sensors do not need to know their geographic positions. Our work is related to theirs in the sense that we maximize the number of parts while trying to reduce the use of the same nodes in these parts. Besides, ours is a deterministic algorithm as opposed to their randomized one and we exclude the assumption that the sensors know their positions.

3 Definitions and Problem Formulation

The sensor network is modelled as a graph $G = (V, E)$, where V denotes the sensors and E represents the links $(u, v) \in E$ between $u, v \in V$ if they are within their transmission range, TR. A sensor monitors a target that falls within its sensing range, SR. For a node u, $N(u)$ defines its neighborhood, i.e., $N(u) = \{v|(u, v) \in E, u \neq v\}$ and $N[u] = N(u) \cup \{u\}$. By $N_f(u)$ we mean the set of nodes which are at most f hops away from u. We use $N(u) = N_1(u)$. Let $T(u)$ represent the set of targets monitored by u. For u and $t \in T(u)$, let $T_t(u)$ represent the set of sensors in $N_2[u]$ that monitors the target t (i.e., $T_t(u) = \{t|t \in T(u) \cap T(v), v \in N_2[u]\}$). Node u maintains an ordered pair at each round i (initially $i = 1$), $p_i(u) = \prec (ct_i(u), id(u)) \succ$, where $ct_i(u)$ (also called the *counter*) denotes the number of monitoring sets in which u has already participated. Initially, $ct_1(u) = 0$ and then for $i > 1$, $ct_i(u) = ct_{i-1}(u) + 1$ if u participates in the monitoring set V_{i-1} in round $i - 1$. The rank $r(X(u))$ of u w.r.t X is the index of u in the lexicographically sorted nodes of X.

We formulate the target monitoring problem in the following way. Given a set of targets $T = \{t_1, \cdots, t_m\}$ and a set sensors $V = \{v_1, \cdots, v_n\}$ (both) randomly and uniformly deployed in the plane such that for each target there is at least one sensor that monitors it, we would like to find a family $\mathcal{V}$ of subsets $V_1, \cdots, V_s$ such that

i) $\forall i$, V_i monitors all targets in T,
ii) $z = s/k$ is maximized, where k=$\max_{v_j \in V} |\{i : v_j \in V_i\}|$.

4 The Algorithm

We present a 2-localized algorithm for the target monitoring problem (assuming now $TR = SR$). Our algorithm works in rounds and at round $i = 1$, node u first forms $T(u)$. Then u sends $T(u)$ and an ordered pair $p_i(u) = \prec (ct_i(u), id(u)) \succ$ to $v \in N_2(u)$ and receives $T(v)$ and $p_i(v)$ from $v \in N_2(u)$. After obtaining $T(v)$ and $p_i(v)$, u forms $T_a(u)$ for each target $a \in T(u)$. Then for each set $T_a(u)$, u computes its rank $r(T_a(u))$ in that round. If u is the smallest ranked node in any set $T_a(u)$, then it becomes active to monitor a, otherwise it goes into the sleep mode. All active nodes in round i are represented by V_i which monitor all the targets. If u becomes active in round i only then its counter is incremented ($ct_{i+1}(u) = ct_i(u) + 1$). Node u then sends $p_{i+1}(u) = \prec (ct_{i+1}(u), id(u)) \succ$ to, and receives $p_{i+1}(v)$ from $v \in N_2(u)$ and a new round $i+1$ starts. The algorithm is given in Figure 1.

4.1 A Problem with Locality

For a subset X_t of nodes that monitor the same target t in some round, it is supposed that the nodes will be in close proximity (due to the spatial correlation). However, the nodes in X_t, although they monitor the same target, can have arbitrarily long hop distance between each other, while the Euclidean distance maybe slightly more than their transmission range. We call this situation the *Locality Effect*, where the monitoring nodes for a certain target do not know about each other about their monitoring.

5 Theoretical Analysis

In this section we give an overview of the theoretical analysis of the algorithm. Consider a target $t \in T$ and let X_t be the set of sensors that monitors it in some round. For a node $u \in X_t$, u knows only whether other nodes, which are within

Input: A connected graph $G = (V, E)$ and a set of targets T s. t. each target is monitored by at least one sensor.

Output: A set of subsets of sensors $V_1, \cdots, V_s$ s.t. each V_i monitors all targets in T.

$i = 1$, send $p_i(u)$, $T(u)$ to $v \in N_2(u)$ and receive $p_i(v)$, $T(v)$
Compute $T_a(u) = \{a | a \in T(u) \cap T(v), v \in N_2(u)\}$, $\forall a \in T(u)$
For round i, compute $r(T_a(u))$, $\forall a \in T(u)$
    If $\exists a \in T(u)$ s.t. $r(T_a(u)) < r(T_a(v))$, $v \in N_2(u)$ **Then**
     u becomes active **Endif**
     $i = i + 1$, **If** u is active **Then** $ct_i(u) = ct_{i-1}(u) + 1$ **Endif**
    If $ct_i(u) \neq ct_{i-1}(u)$ **Then** Send $p_i(u)$ to $v \in N_2(u)$ **Endif**
    Receive $p_i(v)$ from $v \in N_2(u)$
Endfor

Fig. 1. A 2-Localized algorithm for the target monitoring problem

its 2-hop neighborhood (i.e., $N_2[u]$), can monitor t and therefore chooses exactly one among $N_2([u])$ for the monitoring. However, due to the locality effect there can be two nodes $u, v \in X_t$ such that $v \notin N_2(u)$, both u and v monitor t and u does not have any clue about v. We would like to determine an upper bound on how many sensors can monitor a target while none of them is aware of the other. We show that at any round at most five sensors can simultaneously monitor a target, none of which is within the 2-hop neighborhood of the other.

Lemma 1. *For any target $t \in T$, at most five sensors are set as active.*

Proof. Let X_t be the set of sensors that monitors a target $t \in T$ in some round. Suppose for the sake of contradiction that $|X_t| > 5$ and no two nodes $u, v \in X_t$ are within the 2-hop neighborhood of the other. As t is monitored by all sensors in X_t, the Euclidean distance between t and any node $w \in X_t$ must be at most SR. Consider a disk D centered at t with radius equal to SR. Therefore, all the nodes in X_t must be within the disk D. Since $|X_t| > 5$ and nodes of X_t are in D, there will be at least two nodes $u', v' \in X_t$ whose Euclidean distance must be smaller than TR (since $SR = TR$, we can consider TR the radius of D instead of SR). Then u' and v' are direct neighbors to each other, a contradiction. □

Then we derive the corollary from the above lemma.

Corollary 1. *If V_i^* denotes the minimal set of sensors monitoring targets at round i then $|V_i| \leq 5m|V_i^*|$, where $m = |T|$ is the number of targets given.* □

An implication of the above corollary is that if we have a constant number of targets ($|T| = m \leq c$, c is a constant) then we have i.e., $|V_i| \leq 5c|V_i^*|$. So the size of any monitoring set is at most a constant times the size of the minimal monitoring set. Now we show how the algorithm performs towards maximizing the value of $z = s/k$. Denote by z_{opt} the optimal value of z and $z_{opt} > 0$, i.e., $z_{opt} \geq z = s/k$ for all possible values of s and k. If z_{alg} denotes the value of z obtained by the algorithm then we have the following lemma. (Due to the space limitation, please see all the proofs and details in [8])

Lemma 2. *$z_{opt} \leq |X_p|$ and $z_{alg} \geq 1$. Hence z_{opt} is at most $|X_p|$ times the value of z_{alg}.* □

For the following results we assume that the transmission range of a sensor is twice its sensing range, $TR = 2 * SR$.

Lemma 3. *With $TR = 2 * SR$, for any target $t \in T$, exactly one sensor is set as active.* □

We obtain the following corollary from the above lemma.

Corollary 2. *If V_i^* denotes the minimal set of sensors monitoring targets at round i then $|V_i| \leq m * |V_i^*|$, where $m = |T|$ is the number of targets.* □

Now we show that the algorithm obtains the optimal result for maximizing z in special cases. Let $X_1, X_2, \cdots, X_m$ be the subsets of sensors that monitor the targets $t_1, t_2, \cdots, t_m$ respectively in some round, where $X_i \subseteq V$. If $X_i \cap X_j = \phi$, $i \neq j$ then we have the following.

Lemma 4. *With the above assumption and $TR = 2 * SR$, we have $z_{alg} = z_{opt}$.* □

6 Simulation

We conducted extensive simulations on random networks to study the performance of the algorithm. We provide and analyze experimental results regarding (i) maximizing $z = s/k$ and (ii) the size of monitoring sets $|V_i|$. We distribute a set of $m \in \{10, 20, 30, 40, 50\}$ targets randomly in a field of 400m x 400m. Then we generate a random graph G by placing $n \in \{100, 200, 300, 400, 500\}$ nodes uniformly and randomly.

Experiments are done using our own simulator in Java. Setting both SR and TR to 60m, we apply the algorithm with $n = 100$, $m = 10$ and compute the minimum cardinality set X_p and generate $V_1, V_2, \cdots, V_{|X_p|}$. In the experiments, we set $z_{opt} = s/k = |X_p|/1$, since the optimal algorithm can generate at most $|X_p|$ monitoring sets. For z_{alg} we derive the maximum frequency k of a node in X_p in these monitoring sets and obtain $z_{alg} = |X_p|/k$. We generate 100 random graphs successively with the same number ($m = 10$) of randomly distributed targets and for each graph we compute the size of the minimum cardinality set $|X_p|$, maximum frequency k of a node in the monitoring sets and hence obtain z_{opt} and z_{alg}. Finally we obtain the average values of z_{opt} and z_{alg}. Keeping $m =$ 10, we increment the value of n by 100 each time and repeat the whole procedure until $n = 500$. For each pair of $m \in \{20, 30, 40, 50\}$ and $n = \{200, 300, 400, 500\}$, we run the above experiment 100 times and find the averages of the z_{opt} and z_{alg}. The results are plotted in Figure 2, where the x-axis shows the number of targets in the field and the y-axis represents the average values of z_{opt} and z_{alg}.

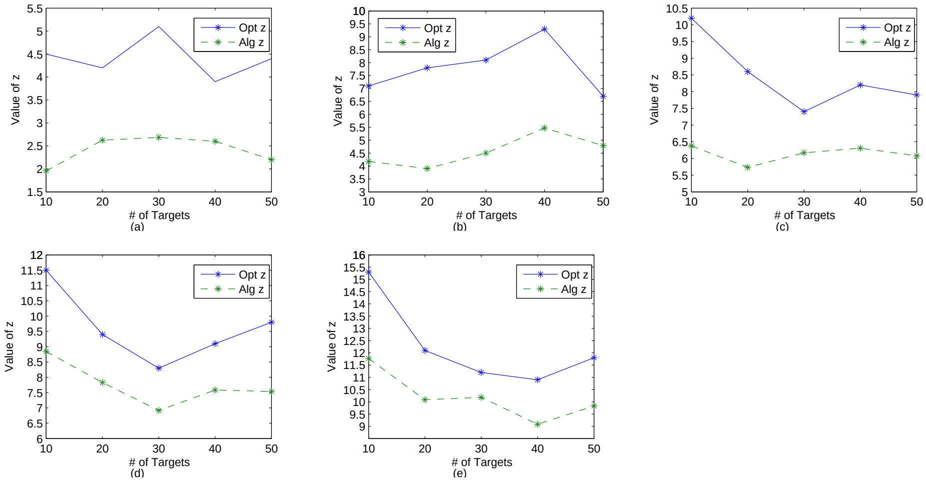

Fig. 2. Average z values (optimal z_{opt} values by solid lines and z_{alg} by dashed lines) for (a) 100 (b) 200 (c) 300 (d) and (e) 500 sensors.

7 Conclusions

In this paper, we have presented a simple 2-localized algorithm to compute a family of monitoring sets such that each set monitors all the targets. We provide theoretical results about the size of monitoring sets, determine bounds on the value of $z(z = s/k)$ when the transmission range is equal to and twice the sensing range. Although the worst-case bound we prove is not appealing (this is because of the fact that the nodes only have very limited information about the topology of the network), we believe it can be improved if nodes have more knowledge about the global topology. We provide simulation results that show much better results than the theoretical bound established in the paper.

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