On Coverage Problems of Directional Sensor Networks*

Huadong Ma[1] and Yonghe Liu[2]

[1] School of Computer Science & Technology,
Beijing University of Posts and Telecommunications, Beijing 100876, China
mhd@bupt.edu.cn

[2] Dept. of Computer Science and Engineering,
The University of Texas at Arlington, Arlington, TX76019
yonghe@cse.uta.edu

Abstract. In conventional sensor networks, the sensors often are based on omnisensing model. However, directional sensing range and sensors are great application chances, typically in video sensor networks. Thus, the directional sensor network also demands novel solutions, especially for deployment policy and sensor's scheduling. Toward this end, this paper evaluates the requirements of deploying directional sensors for a given coverage probability. Moreover, the paper proposes how to solve the connectivity problem for randomly deployed sensors under the directional communication model. The paper proposes a method for checking and repairing the connectivity of directional sensor networks for two typical cases. We design efficient protocols to implement our idea. A set of experiments are also performed to prove the effectivity of our solution. The results of this paper can be also used to solve the coverage problem of traditional sensor networks as a special case.

1 Introduction

Recently sensor networks have attracted tremendous research interests due to its vast potential applications [1, 2, 6, 7]. Conventional sensor networks often assume the omnidirectional sensing model. Actually, directional sensing range and sensors also have great application chances, typically in video sensor networks[14, 15]. Potential applications of video sensor networks span a wide spectrum from commercial to law enforcement, from civil to military. However, many methods for conventional sensor networks is not suitable for directional sensor networks. Thus, the directional sensor network also demands novel solutions, especially for deployment policy and sensor's scheduling.

In our best knowledge, no paper discussed the problems for directional sensor network, although a few papers have indeed studied the concept for video sensor networks [3, 4]. However, the work has mainly focused on low power hardware platform support while system level issues such as QoS capable networking and directional sensing features have been left unaddressed. Therefore, despite half decade of strong progress in sensor design and wireless communications, directional sensor networks remains an unanswered challenge.

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Fundamentally different from conventional sensor networks, directional sensor networks are characterized by its *directional sensing/communicating range*, typically camera's field of view. The feature affects the deployment of sensors, the capture of information and scheduling strategy. These differences are calling for novel approaches for sensor networking. In this paper we take the first step toward a solution for directional sensor networks. In particular, we propose a systematic method for deployment strategy, connectivity checking and repairing, sensor scheduling for randomly deployed directional sensor network.

The reminder of this paper is organized as follows. Related work is discussed in Section 2. In Section 3, we define the sensing model assumed and evaluate the coverage rate of directional sensor network. In Section 4 we discuss the connectivity checking and repairing problem in directional communication model. In Section 5 we describe the scheduling method of directional sensor networks. Experimental results are presented in Section 6 and we conclude the paper in Section 7.

2 Related Work

A lot of pioneer papers address the problem of coverage and connectivity maintenance faced by sensor networks. The common assumption of previous works are that the sensor is omnidirectional sensing/communicating [5, 9, 12, 13, 16, 18]. They can roughly be categorized into the following aspects:

Deployment decision: There are three kinds of deployment policies: regular deployment, planned deployment and random deployment [17]. In the regular deployment method, sensors are placed in regular geometric topology. An example of regular deployment is the grid-based sensor deployment where nodes are located on the intersection points of a grid. An example of planned deployment is the security sensor system used in museums. The most valuable exhibit objects are equipped with more sensors to maximize the coverage of the monitoring scheme. In many situations, deterministic deployment is neither feasible nor practical. The deployment policy often is to cover the sensor field with sensors randomly distributed in the environment. In these cases, the redundancy and density of sensor deployment are problems to focus on.

Sensor Scheduling: One of the main design challenges for sensor network is to obtain long system lifetime without sacrificing system original performance. Since sensors are arbitrarily distributed, sensors' on-duty time should be properly scheduled to conserve energy. Some node-scheduling schemes in [11, 16, 19] are proposed to conserve energy and thus extend the lifetime of the sensor network.

Coverage Completeness: A typical problems is k-coverage problem, whose goal is determine whether every point in the service area of sensor network is covered by at least k sensors. The authors of [8] proposed polynomial-time algorithm to determine k-coverage problem. However, k-coverage problem is formulated as a decision problem, which can only answer a yes/no question. A more general optimization problem is: how can we patch these insufficiently covered areas with the least number of extra sensors. This is still an open question and deserves further investigation. k-coverage is often used to find to the solutions to reliability or fault tolerance, object location, power savings for sensor networks.

Connectivity coverage: Its goal is determine whether every pair of sensors in the service area of sensor network are connected by at least k paths. The problem is how to determine whether the graph is k-connected, and if not, determine how to make the graph k-connected by inserting additional sensors to the network. Solving this problem with a minimum number of additional sensors is NP-hard [10]. The paper [18, 20] discussed how to combine coverage and connectivity maintenance in a single activity scheduling. However, random node deployment often makes initial sensing holes inside the deployed area inevitable even in an extremely high-density network. Therefore, the paper [16] discussed both connectivity maintenance and coverage preservation in wireless sensor networks.

Different from the previous works, this paper mainly focuses on the deployment and scheduling for randomly deployed directional sensor network.

3 Coverage Rate for Directional Sensor Network

3.1 Directional Sensing Models

From the concept of field of view in cameras, we employ a 2-D model where the sensing area of a sensor s is a sector denoted by 4-tuple $(L, r, \boldsymbol{V}, \alpha)$. Here L is the location of the sensor node, r is the sensing radius, $\boldsymbol{V}$ is the center line of sight of the camera's field of view which will be termed *sensing direction*, and α is the offset angle of the field of view on both sides of $\boldsymbol{V}$. Fig. 1 illustrates the directional sensing model. Note that the omni-sensing model is a special case of new model when α is π.

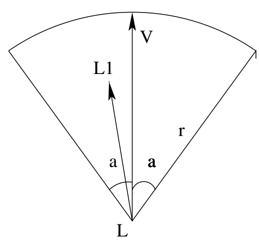

Fig. 1. Directional sensing model

A point L_1 is said to be covered by sensor s if and only if $d(L, L_1) \leq R$, and the angel between $\overrightarrow{LL_1}$ and $\boldsymbol{V}$ is within [-α, α]. An area A is covered by sensor s, if and only if for any point $L \in A$, L is covered by s.

3.2 Coverage Rate for Directional Sensing

In randomly deployed networks, it is hard or impossible to 100% guarantee complete coverage of the monitored region even if the node density is very high. So, it is a practical issue to study how to guarantee the given coverage rate of sensor network for a targeted region.

Assume that the area of the targeted region is S, and the locations of randomly deployed sensors obey uniform distribution. Therefore, after N directional sensors are deployed, the probability of covering the targeted region is represented in Equation (1):

$$p = 1 - (1 - \frac{\alpha r^2}{S})^N \tag{1}$$

For omni-sensing sensors with $\alpha = \pi$, the coverage rate for deploying N sensors is easily obtained by Equation (1).

Thus, if the coverage rate of the targeted region is at least p, the number of deployed directional sensors should be as follows:

$$N \geq \frac{\ln(1-p)}{\ln(S - \alpha r^2) - lnS} \tag{2}$$

For omni-sensing sensors with $\alpha = \pi$, the number of deployed sensors for the given coverage rate p is also obtained by Equation (2).

3.3 Adjustment of Sensing Coverage Rate

The sensing extensions of many sensors, including directional sensor, are adjustable. If the coverage rate must be a given value p in some cases, we can adjust the sensing radius to achieve the goal in Equation (3):

$$r = \sqrt{\frac{S}{\alpha}(1 - (1-p)^{\frac{1}{N}})} \tag{3}$$

In order to minimize the mean energy consumption thus extend the lifetime of sensor network, we can divide *N* sensors into *n* groups, and *n* groups of sensors are working alternatively. The another advantage of grouping working is that each group is activated in different time periods for different monitoring tasks.

According to the conventional model [1, 12], the energy consumption of sensor is in proportion to the k-power of its sensing radius, i.e., $E = Cr^k$, where C is the const and $k \geq 2$.

Theorem 1. When *N* sensors are partitioned into the groups with equal numbers of sensors, the deployment minimizes the energy consumption thus maximizes the lifetime of sensor network.

Proof: Assume that *N* sensors are deployed in the targeted region. We divide them into *n* groups to work alternatively. Their numbers of sensors are $m_1, m_2, \ldots, m_n$, respectively. The sensing radius for each group (denoted as $r_i, i = 1, \ldots, n$) is adopted to meet the coverage rate *p* according to Equation (3).

The energy consumption for a group can be represented as $E_i = n_i C r_i^k (i = 1, \ldots, n)$. Thus, finding the minimum energy consumption reduces to:

$$\min_{\{m_1, m_2, \ldots, m_n\}} \Sigma_{i=1}^n m_i C r_i^k$$

subject to $0 \leq m_i \leq N$ $(i = 1, 2, \ldots, n)$, and $\Sigma_{i=1}^n m_i = N$.

The solution to this problem is $m_1 = m_2 = \cdots = m_n = N/n$. □

4 Connectivity Problem for Directional Sensor Network

4.1 Directional Communication Model

In some cases, the sensor only communicates with others in a specific direction, that is, the sensor is directional sending, and omni-receiving. Shown in Fig. 2, the communication area of a sensor s is a sector denoted by 4-tuple (L, R, $\boldsymbol{D}$, β), where L is the location of the sensor node, R is the communication radius and generally greater than $2r$, $\boldsymbol{D}$ is the center line of the sending field which will be termed *sending direction*, and β is the offset angle of the sending field on both sides of $\boldsymbol{D}$. For the sensors of a directional sensor networks, the sensing direction and communication direction may be same, but communication direction is allowed to be different from sensing directions.

Assume that two sensors can directly communicate if their Euclidean distance is not larger than a communication range R and one node is in the communication area of the other node. We model a directional sensor network as follows:

Definition 1. The directional sensor network can be modelled as a directional communication graph $G(V, E)$ where V is a set of sensors, and E is the edge set. For a pair of node $s_1, s_2 \in V$, the edge $(s_1, s_2) \in E$ if $\|\overrightarrow{s_1 s_2}\| \leq R$ and $\overrightarrow{s_1 s_2} \cdot \boldsymbol{D} \geq \|\overrightarrow{s_1 s_2}\| \cos\beta$, where β is an offset angel of the sensor s_1.

Note that $(s_1, s_2) \in E$ means that s_2 can receive the message from s_1, but s_2 can not send message to s_1 if s_1 is not in the communication area of s_2.

Definition 2. The directional communication graph $G(V, E)$ of a sensor network is said to be *connected to s* if there is a path consisting of edges in E for a given node s and any other sensor s_i in V. The path P for the node s_i and s is represented as $P(s_i, s)$ $=\{(s_i, s_{i+1}), (s_{i+1}, s_{i+2}), \cdots, (s_{i+k}, s)\}$ where $(s_{i+h}, s_{i+h+1}) \in E$ ($0 \leq h \leq k$, s can be renumbered as s_{i+k+1})

Definition 3. Given that a directional communication sub-graph $G_1(V_1, E_1) \in G$ is connected to the node $s \in V_1$, if for any sensor $s_i \in V - V_1$, there is not path between s_i and s, then we call G_1 the maximal connected component to s.

Corollary 1. If $G_1(V_1, E_1) \in G$ is the maximal connected component to s, then for any sensor $s_i \in V - V_1$, there is not a sensor $s_1 \in V_1$ and $(s_i, s_1) \in E$.

Generally, we can find the maximal connected component G_1 to a node s for a directional communication graph G. If the node number of G_1 is equal to that of G, the graph G is connected to s, this is the expected deployment, but is often not true for randomly deployed directional sensor network.

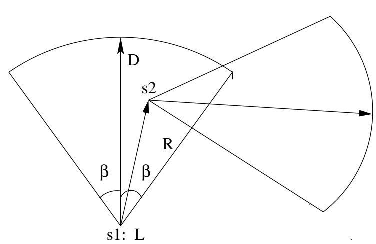

Fig. 2. Directional communication model

Definition 4. For a maximal connected component G_1 to the given sink node x, then we call G_1 *communicable sub-graph*. The other sensors can not communicate with x, they are called *incommunicable sensors*.

4.2 Connectivity Checking

The directional communication graph is a directed graph. First step of our method is to find a maximal connected component C to the given sink node x, and we can use the algorithm *MaxConComp* to find it. Assume that the graph G is represented as adjacency list. The algorithm takes use of depth-first search algorithm.

Procedure MaxConComp(x)

```
//use a visit flag array Visited
1. Visited[x]=TRUE; // the vertex x is visited
2. v:=*x.first; // take the first adjacent vertex
3. while (v is not NULL) do { // if there is adjacent vertex
3.1   if (!Visited[*v.vertex]) MaxConComp(*v.vertex);
3.2   v:=*v.next; //take the next node adjacent to v
3.3   }
```

After we found the maximal connected component C(x) for the sink node x, if the node number of C(x) is less than the node number of G then G is not completely connected to x. For randomly deployed directional sensor network, it is usual that some nodes can not connected to the given sink node x.

4.3 Connectivity Repairing

If there are incommunicable sensors, we need take some measures to make them connected to the sink. Thus, the connectivity repairing is very important for directional sensor network to achieve the monitoring task. Given that the locations of every sensors, we can find the nearest incommunicable node. For repairing connectivity, additional sensors should be added between the communicable component/sink and this incommunicable node. The algorithm is described as follows:

Procedure RepairConnectOne(G,x)

1. C:=MaxConComp(x); //find the maximal connected component
2. G1:=G-C; //take the remaining nodes;
3. while (G1 is not empty) do {

3.1 Find a node x_1 nearest to C in G1, the node nearest to x_1 in C is denoted as y, $d = dis(x_1, y)$;

3.2 Deploy $\lceil \frac{d}{R} \rceil$ sensors with communication radius R,these sensors with the sensing direction $\overrightarrow{x_1 y}$ are equally-spaced deployed between x_1 and y, the first sensor is located in the communicating area of x;

3.3 RepairConnectOne(G1,x_1); // repair the graph G1

3.4 } // end of while

In randomly deployed sensor networks, it is impossible to guarantee the connectivity of the communication graph in the first deployment. The re-deployment for achieving the connectivity is inevitable.

4.4 Grouping Connectivity for Directional Sensor Network

In order to prolong the lifetime of sensor network, we can deploy more than the expected number (N_0) of sensors for a given coverage rate. These sensors will be divided into some groups, each group with N_0 sensors is alternatively activated in turn, to maintain the coverage rate p of the target region.

In this case, we need to ensure each group of sensors are connected. A grouping and connectivity repairing method for directional sensor networks is as follows:

Procedure RepairConnectGroup(G,x)
//find n trees rooted by the node x, all nodes are initiated "not visited"
1. x is the shared root of trees ($T(x, i), i = 1, ..., n$), and marked as "visited";
2. ADJ= the set of nodes adjacent to x;
3. while (there is any not-visited node in G) {
/*Divide ADJ into n groups, and append them to n trees */
3.1 for each node s in ADJ do {
if s is only adjacent to one tree then append s into this tree
otherwise append it into one tree with the minimal number of adjacent nodes in ADJ.
The node s is marked as "visited";
}
3.2 for each tree without adding new node do {
3.2.1 if the node number of $T(x, i)$ is less than $\frac{\|G\|}{n}$ {
3.2.2 Find a pair of nodes with the nearest distance between $T(x, i)$ and
the not-visited nodes of G, denoted as (A,B) where $A \in T(x, i)$
and B is not visited;
3.2.3 B is marked as "visited", $d = dist(A, B)$;
3.2.4 Deploy $\lceil \frac{d}{R} \rceil$ sensors, these sensors with the sensing
direction $\overrightarrow{BA}$ are equally-spaced deployed between B and A,
the first sensor is located in the communicating area of B;
3.2.5 } //end of if
3.3 } //end of for
3.4 ADJ:= the set of not-visited nodes adjacent to the nodes of ADJ
3.5 } //end of while

5 Scheduling for Directional Sensor Network

5.1 Basic Idea

We propose a coverage and connectivity maintenance scheme for randomly deployed directional sensor networks, which works in three phases as follows.

Deployment: The directional sensors are randomly deployed for monitoring a targeted region. According to the analytical result of Section 3, we can calculate the required number of deploying sensors for the expected coverage rate.

Checking: During the checking phase, each sensor node find its own position and synchronizes time with neighboring nodes, and ready for sensing. The system will check the connectivity of deployed sensors, and if the sensor network is not connected then repair it for achieving the connectivity.

Sensing: The sensor network starts to execute sensing task according to the scheduling policy. Each sensor starts detecting the environmental events. Each node will establish a working schedule through our methods, which tell it when to sleep and when to work for each round. When a node goes to sleep, its sensing, computation and communication components can all be asleep and only a timer needs to work and wake up all components according to scheduling policy.

5.2 Scheduling Protocols

Assume that N_0 is the number of sensors for achieving the required coverage rate p under the sensing radius r and the communication radius R. We design two node scheduling schemes for directional sensor networks.

Simple Scheduling Protocol. We deploy N_0 sensors randomly in the targeted region; and call *RepairConnectOne* for checking and repairing the connectivity of N_0 sensors; then the sensor network begins working, all sensors are active until the sensor network is used up.

Grouping Scheduling Protocol. We take N sensors ($N = n * N_0$) to cover the targeted region. These sensors are divided into n groups in which there are N_0 sensors. These n groups are alternatively activated in turn, to maintain the coverage rate p of the target region for nT_0 time (T_0 is the lifetime of a group). Thus, the grouping scheduling protocol is presented as follows.

/* Deployment*/
1. Calculating the number of required sensors (N_0) for the coverage rate p;
2. Input the expected lifetime of the sensor network, i.e., T;
3. Take $n(=\lceil \frac{T}{T_0} \rceil)$ groups of sensors, each group consists of N_0 sensors;
4. Deploy N (=$n * N_0$) sensors randomly in the targeted region,
   get the directional communication graph G for this deployment;

/* Grouping and repairing */

5. Call RepairConnectGroup(G,x);// x is the sink node.
6. Set the starting time of sensors in i-th group is set to $(i-1)T_0$;

/* Scheduling sensor groups */

7. The sensor network begins working, the timer is counting from 0;
8. The first group of N_0 sensors is active at the time 0;
9. After T_0 time is passed, a new group (if there is) will be active
   until n groups of sensors have been used up.
10. End.

6 Experimental Results

6.1 Simulations

We want to verify our theoretic analysis for the relationships among the coverage rate p, the sensor number N, the offset angel α, and the sensor radius r.

We studied the coverage rate of the target region of 500*500 m^2 in our simulation. The number of randomly deployed sensors is varied from 0 to 1500. The offset angel of

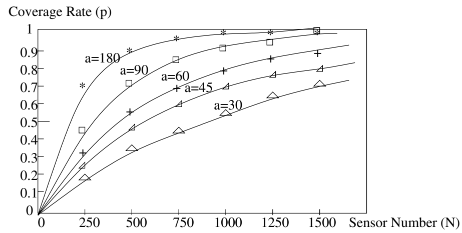

Fig. 3. The effect of the sensor number

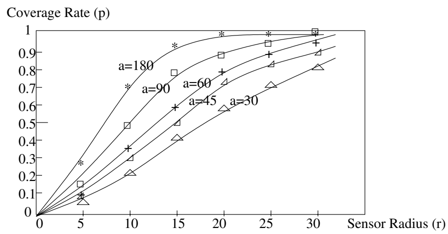

Fig. 4. The effect of the sensing radius

directional sensor (α) is varied from 0 to 180 (π), and the sensor radius is changed from 0 to 25m. The simulations was executed in OPNET platform. All simulation results are closely match with the theoretical analysis in Section 3.

We first consider the effect that sensor number make to the coverage rate. Fig. 3 shows that the greater the sensor number (N), the greater the coverage rate p becomes. In other words, the coverage rate will increase with the increasing of sensor number. We also examined the effect of the sensing radius for coverage rate. Fig. 4 shows the relationship between the coverage rate p and the sensing radius r. It indicates that the greater the sensing radius is, the greater the coverage rate p becomes.

6.2 Case Study

We use a case to illustrate the effectiveness of coverage and connectivity maintenance for randomly deployed directional sensor networks. In a 500*500 m^2 field, we want to deploy the video sensors with the sensing radius 50m and the offset angel $90(\frac{\pi}{2})$ for gathering the visual information. If the required coverage rate is at least 85%, we can calculate the sensor number to be deployed: N=87.

Assume that the lifetime of sensor is 50 hours. The expected lifetime of network is 150 hours, thus we can take 3*87=261 sensors to randomly deploy in the targeted region. A distribution of deployed sensors is generated.

We use grouping scheduling protocol to demonstrate the coverage and connectivity maintenance for this deployment. 261 sensors are divided into 3 groups in which there are at least 87 sensors with the sensing radius $50m$ and the communication radius $100m$, the additional 3 nodes and 5 pathes are re-deployed for repairing the connectivity of 3 groups. These 3 groups are alternatively activated in turn, to maintain the coverage rate 85% of the target region for 150 hours. The deployment and its distribution state of repaired grouping connectivity are not presented here because of the limit of page space.

7 Conclusions and Future Work

Different sensing model of directional sensor networks demands efficient methods for deployment policy and connectivity maintenance. Motivated by this, this paper proposes a systematic method for coverage and connectivity of randomly deployed directional sensor networks. By quantifying the requirements of deploying sensors for a given coverage rate, we can decide the deployment policy. Moreover, we model the directional sensor network as a directed communication graph to analyze its connectivity, and repairing the connectivity of a randomly deployed directional sensor network. Based on the theoretic works, we design the sensor deployment and scheduling protocols for the application of directional sensor networks. The methods are shown to be highly efficient and feasible for applications of directional sensor works.

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