Some problems of directional sensor networks

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Abstract: Wireless sensor networks are often based on omni-sensing and communication models. In contrast, in this paper, we investigate sensor networks with directional sensing and communication capability. Due to the distinct characteristics and potential effects on coverage and connectivity of the network, novel analysis and solutions are demanded. Toward this end, this paper analyzes deployment strategies for satisfying given coverage probability requirements with directional sensing models. Moreover, for sensors with directional communication model, we propose methods for checking and repairing the connectivity of the network. We design efficient protocols to implement our idea. A set of experiments are also performed to prove the effectiveness of our solution.

Keywords: Coverage; Connectivity; Scheduling; Directional sensor networks.

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1 INTRODUCTION

Wireless sensor networks have attracted tremendous research interests due to its vast potential applications (1; 2; 7; 8; 18). In these networks, an omnidirectional sensing model is often assumed where each sensor can equally detect its environment in each direction. Instead, in this paper, we focus on sensor networks with directional sensing range. Our motivation is the recently emerged video sensor networks as discussed in (17; 15), whose potential applications 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. Fundamentally different from conventional sensor networks, directional sensor networks are characterized by its *directional sensing/communicating range*. This unique feature can fundamentally affect the deployment of sensors, the capture of information, and scheduling strategy.

To the best of our knowledge, there has been no existing work on directional sensor network. Although a few papers have indeed studied the concept for video sensor networks

(3; 4), they mainly focused on the hardware platform while system level issues such as QoS capable networking and directional sensing features have been left unaddressed.

In this paper we take the first step toward a solution for directional sensor networks. In particular, we propose a systematic method for deploying sensor nodes with directional sensing range, and subsequent connectivity checking and repairing. We first derive the conditions to satisfy certain coverage requirement for randomly deployed directional sensor networks. For senor nodes with adjustable sensing range, we also provide the optimal deployment strategy that will maximize the lifetime of the network. We then model the directional sensor network as directed communication graph, and employ directed graph theory to study the connectivity checking and repairing problems. The result is an efficient method for scheduling and connectivity maintenance for directional sensor networks. Finally, we design efficient protocols to implement our ideas and provide a set of experiments to validate our solution.

The reminder of this paper is organized as follows. Related work is discussed in Section 2. In Section 3, we define the directional sensing model and study the coverage problem. In Section 4, we discuss the connectivity checking and repairing problem with 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 in Section 7.

2 Related work

While the assumption of omnidirectional sensing range has facilitated elegant properties of conventional sensor networks (6; 10; 14; 16; 19; 22), directional sensor is characterized by its *directional sensing/communicating range*. This characteristic introduces fundamentally different properties in terms of network coverage and connectivity maintenance targeted by this paper.

Extensive work has addressed the problem of coverage and connectivity maintenance in wireless sensor networks. From the perspective of sensing, coverage requirement denotes that the deployment of sensors must cover the whole monitored area to a certain extent. From the perspective of communication, connectivity requirement denotes that the deployed sensors must be capable of communicate with each other either directly or through multiple hops. It has been the common assumption of previous works that the sensors are omnidirectional sensing and communicating. Below, we provide an brief overview of existing work.

Deployment Strategies: Generally sensor nodes can be deployed in three different way: regular deployment, planned deployment, or random deployment (21). In regular deployment, sensors are placed in regular geometric topology. An example of regular deployment is the grid-based approach where nodes are located on the intersection points of a grid. Planned deployment can be exemplified by the security sensor systems used in museums. In these systems, the most valuable exhibit objects are equipped with more sensors to maximize the coverage of the monitoring scheme. An important problem for planned deployment is to minimize the number of sensors required for covering the sensing area. Regarding this, the widely studied Art Gallery problem investigates the number of observers necessary to cover an art gallery such that every point is monitored by at least one observer. It has been shown that this problem can be solved optimally in a 2D plane but it is NP-hard when extended to a 3D space. 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. The stochastic random distribution scheme can be uniform, Gaussian, Poisson or any other distribution dependent on the applications. In those cases, the redundancy and density of sensor deployment are problems to focus on.

Sensor Scheduling: A key challenge for sensor network is to extend the network lifetime in the resource limited environment. As sensors are often densely distributed, they can be scheduled on alternative duty cycles in order to preserve energy while satisfying the system requirements. Intuitively, if certain sensors share common sensing region and tasks, some of them can be switched into sleep mode to conserve energy. A probing-based density control algorithm is proposed in (23) to schedule sensor nodes. In this protocol, a subset of nodes is selected initially and is maintained in working mode until they run out of energy. Other redundant nodes are allowed to fall asleep and required to wake up occasionally to probe their local neighborhood. Sleeping nodes start working only if there is no working node within its probing range. In this algorithm, geometry knowledge is used to calculate the value of probing range as a function of redundancy. As a result, desired redundancy can be obtained by choosing the corresponding probing range. Another node-scheduling scheme is proposed in (20) to reduce system overall energy consumption. In this scheme, the coverage-based off-duty eligibility rule and backoff-based node-scheduling scheme guarantee that the original sensing coverage is maintained after turning off redundant nodes. Several alternative node-scheduling schemes called *neighbor-number-based*, *nearest-neighbor-based* and *probability-based* node-scheduling schemes are proposed in (19). These schemes cannot completely preserve the original system coverage, but are nonetheless light-weighted and flexible as compared with the previous one. They are all location-free and calculation-free. The basic idea is that before scheduling, users can select a desired coverage percentage loss; then a corresponding threshold, i.e., the minimal neighbors' number K, the nearest neighbor distance D, or the probability p, is calculated by using a given expression or prior collected data pairs; during the scheduling period, each node can determine its desired status based on the adopted threshold value. Several ILP (Integer Linear Program) formulations and strategies are presented in (13) to reduce overall energy consumption while maintaining guaranteed 0/1 coverage levels.

Coverage: Coverage can be considered as a measurement of the quality of service provided by the wireless sensor networks. A typical problems is k-coverage problem, whose goal is to determine whether every point in the monitored area is covered by at least k sensors. A polynomial-time algorithm to determine whether the network provides k-coverage is proposed in (9). The basic idea behind the algorithm is to focus on the perimeter of each sensor's sensing range. As long as the perimeters of the sensors are covered, the whole area is sufficiently covered. The solution can be easily translated to distributed protocols where each sensor only needs to collect local information to make its decision. k-coverage is often discussed in the context of reliability or fault tolerance.

Connectivity: In the ad-hoc environment of wireless sensor networks, connectivity is of particular importance for maintaining communications among the sensor nodes. The k-connectivity problem targets at determining whether every pair of sensors in the targeted area is connected by at least k paths and if not, how additional sensors can be deployed to achieve the goal. This problem has been proven to be NP-hard (11) if a minimum number of additional sensors is targeted. Indeed, coverage and connectivity are closely coupled issues. Approaches on combining coverage and connectivity maintenance under a single activity scheduling is discussed in (22) and (24). It is also discussed in (19) on concurrent connectivity maintenance and coverage preservation in wireless sensor networks.

Different from existing work, this paper mainly focuses on the deployment and scheduling for randomly deployed directional sensor nodes. Evidently, the results also apply to coverage preservation and connectivity maintenance for omnidirectional sensor network as a special case.

3 Coverage Problem with Directional Sensing

3.1 Directional Sensing Model

Different from conventional sensing models where an omni-sensing area centers on the sensor node, we employ a directional sensing model. An analogy can be found in the concept of field of view in cameras (5).

We consider a 2-D model where the sensing area of a sensor s is a sector denoted by 4-tuple $(L, r, \vec{V}, \alpha)$. Here L is the location of the sensor node, r is the sensing radius, $\vec{V}$ 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 $\vec{V}$. Fig. 1 illustrates the directional sensing model. Note that the conventional omni-sensing model is a special case of new model when α is π.

A point L_1 is said to be covered by sensor s if and only if the following conditions are met:

1. $d(L, L_1) \leq R$, where $d(L, L_1)$ is the Euclidean distance between the location L of sensor s and point L_1.

2. The angle between $\overrightarrow{LL_1}$ and $\vec{V}$ is within $[-\alpha, \alpha]$

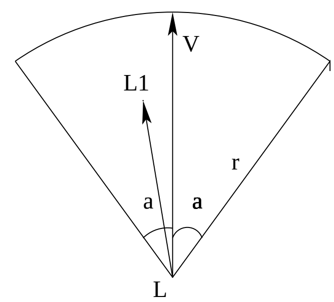

Figure 1: Directional sensing model

A simpler method to judge if point L_1 is covered by directional sensor s is as follows: if $\|\overrightarrow{LL_1}\| \leq r$ and $\overrightarrow{LL_1} \cdot \vec{V} \geq \|\overrightarrow{LL_1}\| \cos\alpha$, L_1 is covered and otherwise not. 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 under Directional Sensing Model

For sensor networks formed by random deployment, for example, dropped by an airplane, it is difficult, if not impossible, to guarantee 100% coverage of the monitored area even if the node density is very high. Our focus in investigating the coverage problem in directional sensor networks is then set to be probability guarantee.

Assume that the area of the monitored region is S, and there are no two sensors located at exactly the same position and sensing region. Notice that a directional sensor with offset angle α covers a sensing area of αr^2. Assume that the sensors are randomly deployed in the monitored region, and the locations of sensors obey uniform distribution. After N directional sensors are deployed, the probability that the targeted region is covered is given by

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

Notice that for omni-sensing sensors with $\alpha = \pi$, the coverage probability for deploying N sensors is simply

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

Naturally, if the coverage probability of the targeted region is required to be at least p, the number of deployed directional sensors should be

$$N \geq \frac{\ln(1-p)}{\ln(S - \alpha r^2) - lnS}. \tag{3}$$

Again, for omni-sensing sensors with $\alpha = \pi$, the number of sensors required for the given coverage probability p should be

$$N \geq \frac{\ln(1-p)}{\ln(S-\pi r^2) - lnS}. \quad (4)$$

From the above equations, to achieve the same coverage probability, the ratio between the numbers of directional sensors and omni-sensing sensors required is given by

$$M = \frac{\ln(S-\pi r^2) - lnS}{\ln(S-\alpha r^2) - lnS}. \quad (5)$$

3.3 Adjustable Sensing Range

We further extend the above model to be adjustable and naturally various sensing range will consume different energy.

In this case, if the number of deployed sensors is fixed, we can adjust sensors' sensing range in order to satisfy the coverage requirement. Assume that the number of sensors is N. We can easily draw the relationship between p and r from Equation (1). On the other hand, if the coverage problem must satisfy a given value p , we can adjust the sensing radius to achieve the goal according to Equation (6) and the radius r should be

$$r = \sqrt{\frac{S}{\alpha}(1-(1-p)^{\frac{1}{N}})} \quad (6)$$

According to (1; 14), the energy consumption of a sensor is in proportion to the k-power of its sensing radius, i.e.,

$$E = Cr^k, \quad (7)$$

where C is a constant, and $k \geq 2$.

To extend the network life time, often sensors are partitioned into different groups and their awake times will be alternated. This way, one group of sensors will be performing the sensing task while other groups remain asleep. Obviously, for each individual group, the coverage requirement has to be satisfied as well. With adjustable sensing ranges, each group of sensors does not necessarily need to be equal in numbers, as the required coverage can be achieved by tuning the sensing range of each sensor as well. Our next interests to determine the optimal partition of sensors under this group based scheduling, given N directional sensors and the required coverage probability p. Our goal is to minimize the total energy consumption and hence maximize the network life time. For this, we have the following theorem.

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

Proof: Assume that N sensors are deployed in the targeted region. We will divide those sensors into n groups to work alternatively. Their numbers of sensors are denoted by $m_1, m_2, \ldots, m_n$, respectively. The sensing radius for each group, denoted by $r_i, i = 1, \ldots, n$, is adopted to meet the coverage probability p according to Equation (6).

Calculating 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 is reduced 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 $m_1 = m_2 = \cdots = m_n = N/n$. □

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4 Connectivity Problem with Directional Communication

4.1 Directional Communication Model

In this section, we employ a directional communication model for directional sensor network to investigate the connectivity isssue. In this model, a sensor only communicates with others residing in a specific direction,. Each sensor is directional sending and omni-receiving. Mathematically, the directional communication model is similar to the sensing model and is shown in Fig. 2.

The communication area of a sensor s is a sector denoted by 4-tuple (L, R, $\vec{D}$, β), where L is the location of the sensor node, R is the communication radius, $\vec{D}$ 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 $\vec{D}$. For sensors with both directional sensing and communication, the sensing direction and communication direction are allowed to be different in this paper.

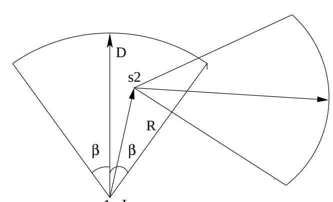

Figure 2: Directional communication model

We assume that two sensors can directly communicate if their Euclidean distance is not larger than the 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. A sensor network can be modeled as a directional communication graph $G(V, E)$ where V is the set of sensors in the network, and E is the edge set between them. For a pair of node $s_1, s_2 \in V$, edge $(s_1, s_2) \in E$ if $\|\overrightarrow{s_1 s_2}\| \leq R$ and $\overrightarrow{s_1 s_2} \cdot \vec{D} \geq \|\overrightarrow{s_1 s_2}\| \cos\beta$, where β is the offset angle of sensor s_1. Notice that $(s_1, s_2) \in E$ means that s_1 can send message to s_2 and s_2 can receive the message from s_1, but s_2 cannot 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 between a given node s and any other sensor s_i in V. The path P between s_i and s can be 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 node $s \in V_1$, if for any sensor $s_i \in V - V_1$, there is not a path between s_i and s, we call G_1 the maximal connected component (sub-graph) to s.

Given the above model and definitions, we have the following lemma.

Lemma 1 If $G_1(V_1, E_1) \in G$ is the maximal connected component (sub-graph) to s, for any sensor $s_i \in V - V_1$, there doe exist a sensor s_1 satisfying $s_1 \in V_1$ and $(s_i, s_1) \in E$.

Proof: We will use contradiction. For any sensor $s_i \in V - V_1$, if there is a sensor $s_1 \in V_1$ and $(s_i, s_1) \in E$, there is a path $P(s_i, s)$= $\{(s_i, s_1), P(s_1, s)\}$ where $P(s_1, s)$ is the path between s_1 and s because node s_1 is connected to s. Thus, s_i is connected to s. Therefore, $G_1(V_1, E_1)$ is not the maximal connected component to s.

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, graph G is connected to s. This is the desired deployment and connectivity. However, often the node number of G_1 is less than that of G for randomly deployed directional sensor network.

Definition 4. For a maximal connected component G_1 to the given sink node x, we call G_1 *communicable subgraph*. Other sensors that cannot communicate with x are called *incommunicable sensors*.

Notice in this case only connected sensors can report data to the sink. If G_1 is the maximal connected component in G and its number of sensors is N_1, the effective coverage probability for such deployment is reduced to

$$p_e = 1 - (1 - \frac{\alpha r^2}{S})^{N_1}. \quad (8)$$

4.2 Connectivity Checking

Our next step is to design some algorithms to check the connectivity for a directional communication graph.

A directional sensor network can be viewed as a directed graph. The first step of our method is to find the maximal connected component C to the given sink node x, and the corresponding algorithm *MaxConComp* is described in Table 1. Assume that the graph G is represented as an adjacency list. The algorithm uses depth-first searching.

After we found the maximal connected component C(x) for the sink node x (the nodes of C(x) are the node marked with "visited"), if the node number of C(x) is less than the node number of G, G is not completely connected to x. For randomly deployed directional sensor networks, it is usually common that some nodes can not connected to the given sink node x so that the graph G is not completely connected to x.

Table 1: Maximum Connected Component

```
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);
       //if the vertex is not visited, call MaxConComp for it
3.2    v:=*v.next; //take the next node adjacent to v
3.3    }
```

4.3 Connectivity Repairing

If there are sensors not connected to the sink, it is to the best interests of the network to perform repairing and enable the communication. We next propose a repairing method for this purpose.

Assume that the locations of the sensors are known. We can locate sensors not connected in the network. For repairing purpose, additional sensors should be added between the communicable component/sink and incommunicable nodes. We propose an algorithm towards this end in Table II.

Table 2: Connectivity Repairing for One Graph

Procedure RepairConnectOne(G,x)
1. C:=MaxConComp(x);
   //find the maximal connected component for x
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, $d = dist(x_1, y)$;
3.2 Deploy $\lceil \frac{d}{R} \rceil$ sensors with communication radius R, those 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);
   //call RepairConnetOne to repair the graph G1
3.4 } // end of while

In randomly deployed sensor networks, it is hard to guarantee the connectivity of the communication graph after initial deployment, repairing is often desirable. Fig.3 provides an illustration of connectivity repairing for directional sensor networks.

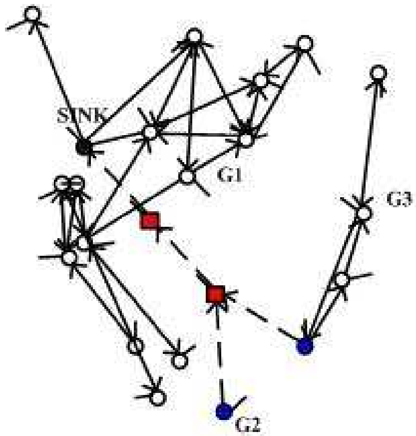

Figure 3: Repaired connectivity

4.4 Grouping and Repairing Connectivity for Directional Sensor Network

In order to prolong the lifetime of a sensor network, we can deploy more than the expected number (N_0) of sensors for a given coverage probability. Those sensors will then be divided into groups, each group with N_0 sensors is alternatively activated to maintain the coverage probability p of the targeted region. At the same time, we also need to ensure each group of sensors is connected. The key problem then is how to divide the sensors to make all sensors connected to the sink in each group. And if incommunicable node exists, repairing shall be performed in order to enhance its connectivity. For this, a grouping and connectivity repairing method for directional sensor networks is given in Table 3.

Table 3: Grouping and Connectivity Repairing Algorithm

Procedure RepairConnectGroup(G,x)
//find n trees rooted by the node x, use a visit
// flag array, all nodes are initiated "not visited"
1. x is the common roots of $T(x, i)(i = 1, .., n)$,
and marked as "visited"; // the node x is 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 } //end of if
3.5 ADJ:= the set of not-visited nodes adjacent to
the nodes of current ADJ
3.6 } //end of while
4 End.

5 Scheduling for Directional Sensor Network

Directional sensor networks also face the critical challenge of sustaining long-term operation on limited battery energy. Sensor scheduling protocols can effectively prolong network lifetime by maintaining sufficient sensing coverage over a region using a small number of active nodes. In this section we present some coverage and connectivity maintenance protocols to schedule the directional sensors for practical applications.

5.1 Basic Idea

We divide the operation of a sensor network into three phases: the deployment phase, the checking phase and the sensing phase. In each phase, the coverage and connectivity maintenance can be summarized as follows.

Deployment: Directional sensors are randomly deployed for monitoring a targeted region. According to the analytical result of Section III, we can calculate the required number of sensors for the expected coverage probability.

Checking: During the checking phase, each sensor node perform localization and synchronization. The system will check the connectivity of deployed sensors, and perform connectivity repairing if needed.

Sensing: The sensor network starts to execute sensing tasks according to the scheduling policy. Each node will establish a working schedule which dictates the sleep/wakeup pattern.

Assume that the deployment of N sensors can achieve the coverage probability p for the targeted area. Obviously, if we increase the number of deployed sensors, the coverage probability will be increased, or alternatively the lifetime of sensor network will be prolonged once a suitable scheduling policy is taken. The increasing of coverage probability can be quantified according to the analysis of Section III.

5.2 Scheduling Protocol

We design two node scheduling schemes for directional sensor networks in order to extend the lifetime of a sensor network.

Simple Scheduling Protocol. Assume that N_0 is the number of sensors for achieving the required coverage probability p when each sensor has sensing radius r_0 and communication radius R. We deploy N_0 sensors randomly in the targeted region; and *RepairConnectOne* is executed for checking and repairing the connectivity of these N_0 sensors. Then, the sensor network begins working and all sensors remain active until the sensor network dies.

Grouping Scheduling Protocol. Assume that N_0 is the number of sensors for achieving the required coverage probability p when each sensor has sensing radius r_0 and communication radius R. We deploy N sensors ($N = n * N_0$) to cover the targeted region. and divide the set of sensors into n groups, each with N_0 nodes. These n groups are alternatively activated to maintain the coverage probability p of the target region for nT_0 time period where T_0 is the lifetime of a group. In this protocol, we can use the grouping and connectivity repairing algorithm in Section IV. This grouping scheduling protocol is presented in Table 4.

Table 4: Grouping Scheduling Protocol

/* Deployment*/

1. Calculating the number of required sensors (N_0) for a given coverage probability 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, where each of the groups consists of N_0 sensors with the sensing radius r_0 and the communication radius R.
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 $(i-1)T_0$ $(1 \leq i \leq n)$;

/* 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

In this section, we verify our theoretic analysis.

Table 5: Parameters setting

Parameter	Default	Variation
Coverage rate p	1	0-1
Sensor number N	1000	0-1500
Offset angle α	180	0-180
Sensor radius	20m	0-25m
Communication radius	40m	0-50m
Area S	500*500m^2	500*500m^2

We studied the coverage probability of a region of 500*500 m^2 in our simulation. The number of randomly deployed sensors is varied from 0 to 1500. The offset angle of directional sensor is varied from 0 to 180 (π), and the sensor radius is changed from 0 to 25m. The simulations is executed in OPNET. The simulation parameters are summarized in Table 5.

We first consider the effect of the number of sensors to the coverage rpobability. Fig. 4 shows that the larger the sensor number (N) is, the higher the coverage probability p becomes. In other words, the coverage probability will increase with the increasing of number of nodes.

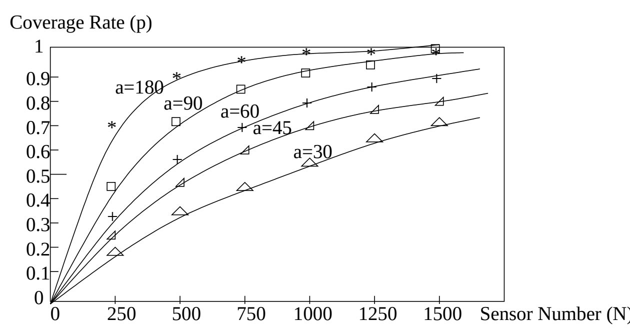

Figure 4: The effect of the sensor number

We also examined the effect of the sensing radius. Fig.5 shows the relationship between the coverage probability p and the sensing radius r. It indicates that the larger the sensing radius is, the higher the coverage probability p becomes.

We also evaluated the relationship between the coverage probability and the offset angle. For 1000 sensors, Fig. 6 shows the coverage probability that different offset angles will achieve. Moreover, for the same region, if the coverage probability of a directional sensor network is the same as the achievable coverage probability of N omnidirectional sensors, the number of deployed directional sensors M is

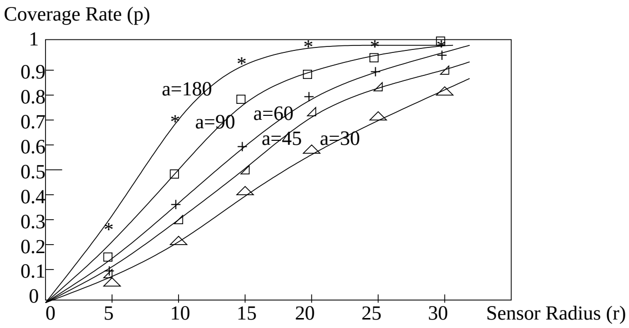

Figure 5: The effect of the sensing radius

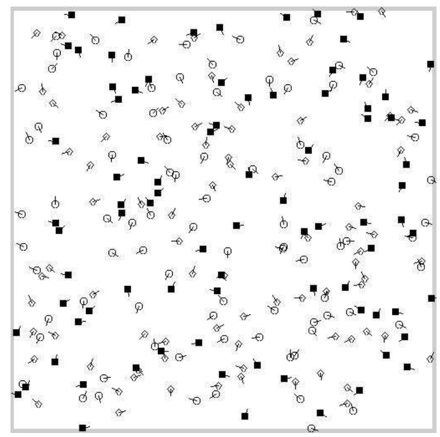

Figure 8: A distribution of deployed sensors

evaluated. Fig.7 shows the relationship between the offset angle α and the factor $f = \frac{M}{N}$.

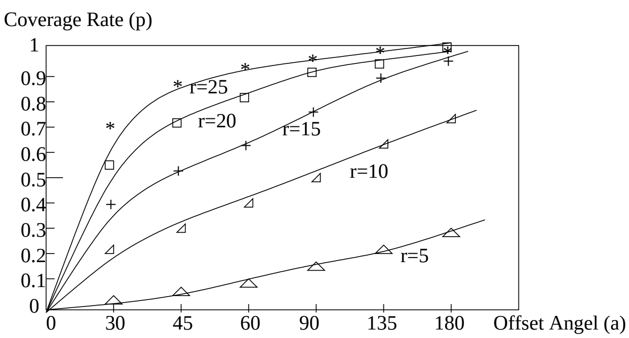

Figure 6: The effect of the offset angle

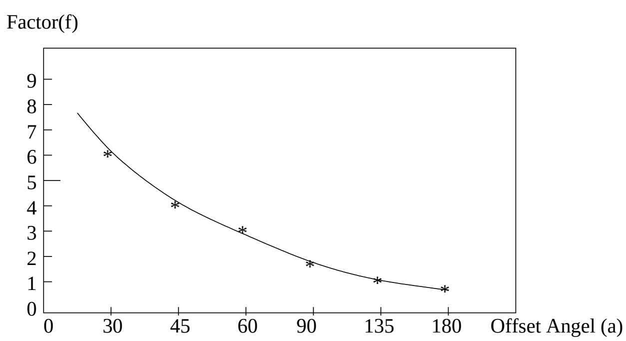

Figure 7: The number factor for different offset angle

6.2 Case Study

We use an example here to illustrate the effectiveness of coverage and connectivity maintenance for randomly deployed directional sensor networks.

In a 500*500 m^2 field, we deploy sensors with sensing radius 50m and offset angle $90(\frac{\pi}{2})$ for gathering. If the required coverage probability is at least 85%, we can calculate the sensor number to be deployed as follows:

$$N = \frac{ln(1 - 0.85)}{ln(250000 - 1250\pi) - ln(250000)} = 87$$

Assume that the lifetime of a sensor is 3000 minutes (50 hours). The expected lifetime of the network is 9000 minutes (150 hours), thus we can take 3*87=261 sensors to be randomly deployed in the targeted region. A distribution of deployed sensors is presented in Fig.8.

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 paths are re-deployed for repairing the connectivity of 3 groups. These 3 groups are alternatively activated, to maintain the coverage probability 85% of the target region for 150 hours. Fig.9 illustrates the distribution of the grouping scheduling. Fig.10 illustrates the distribution of repaired grouping connectivity.

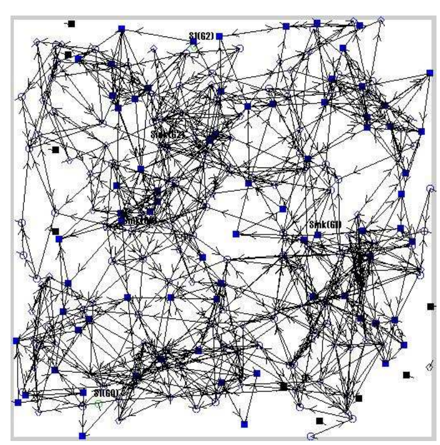

Figure 9: The grouping scheduling

7 Conclusions and Future Work

Directional sensor networks demand efficient methods for deployment policy and connectivity maintenance. Motivated by this, this paper systematically investigates the coverage and connectivity problems of randomly deployed

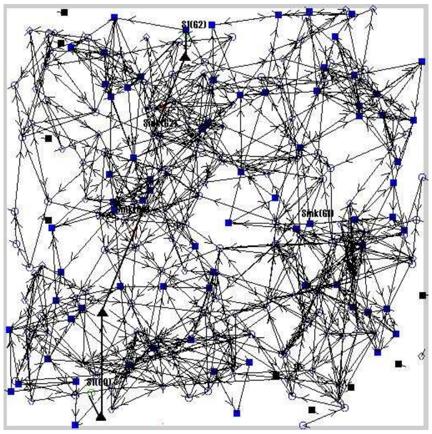

Figure 10: Repaired grouping connectivity

directional sensor networks. For a given coverage probability, we investigate the deployment policy to satisfy the requirement. We also model the directional sensor network as a directed communication graph to analyze its connectivity, and repairing policy. Based on the theoretic works, we have designed deployment and scheduling protocols. The methods are shown to be highly efficient and feasible for applications of directional sensor works through simulations.

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