

Coverage Algorithm and Protocol in Heterogeneous Sensor Networks

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Abstract. One fundamental issue in wireless sensor networks is the coverage problem. In heterogeneous sensor networks composed of different types of sensors, the difference of the sensing radius of nodes augments the computation difficulty of coverage degree. In this paper, we analyze the features of heterogeneous sensor networks and discuss the approaches to guarantee and calculate the coverage degree of the region deployed by heterogeneous sensor networks. Based on our analysis, a *Distributed Coverage Optimization Algorithm* by which each node in the network can determine whether it should be turn active/inactive is proposed. Simulation shows that our algorithm can make the extraneous nodes inactive and minimize the number of nodes need to remain active.

1 Introduction

Recently, the research of wireless sensor networks has attracted more and more attention due to the wide-range of potential applications that will be enabled by such networks. In wireless sensor network, energy efficiency is a key research problem because the battery power of an individual sensor node is severely limited and can not be replaced due to the remote and hazardous monitoring scenarios of sensor networks, such as ocean floor and battlefield. However, the system lifetime of sensor networks, which is measured by the time till all nodes have been drained out of their battery power or the network no longer provides an acceptable event detection ratio [1], is always expected relative long by many sensing applications.

Extending research and simulation have showed that significant energy savings can be achieved by dynamic management of node duty rounds in sensor networks of high node density. It is important for a sensor network to assign the extraneous nodes an off-duty operation mode and minimize the number of nodes on duty while still achieving acceptable quality of service, in particular, satisfying the sensing coverage requirements of applications. Different applications require different degrees of sensing coverage. For example, target surveillance may only require that every location in the sensing region be monitored by one node, while target localization and tracking require at least three coverage degrees [2] [3]. Recent three years, the problem of sensing coverage has been investigated extensively, several coverage schemes and proto-

cols have been addressed. In [4], adjustable probing range and wakeup rate of sensor nodes were adopted to control the degree of sensing coverage. Literature [5] proposed a distributed node-scheduling algorithm, in which each node arithmetically calculates the union of all the sectors covered by its neighbors and determines its working status according to the calculation result. In [6], a differentiated surveillance scheme was presented, the scheme schedules the sensing phase of each node and makes all the nodes work alternatively to achieve the energy balance of the network. Literature [7, 8] addressed how to combine consideration of coverage and connectivity maintenance in a single activity scheduling.

However, most of coverage schemes can only be applied to the homogeneous sensor networks. Based on the analysis of the heterogeneous sensor networks, we proposed a *Distributed Coverage Optimization Algorithm, DCOA* by which each node in the network can determine whether it should be turn active/inactive.

2 Characters of H eterogeneous Sensor Networks

2.1 Heterogeneous Sensing Model

Heterogeneous sensor network is such a network which consists of sensors with different functions and different sensing ranges. In this paper, we define A as the convex region where sensor nodes are deployed in, $Bond(A)$ as the boundary of region A . Assume each kind of nodes can do 360° observation, for any sensor s in the node set S , We define the boundary of s 's coverage region as a circle $C(s)$, the radius of $C(s)$ as the sensing range of s , denoted by $Rs(s)$. We also define $Rc(s)$ as the maximal communication radius of s . In order to guarantee the connectivity of the network, we assume that for any pair of sensors $s_1, s_2 \in S$, $Rc(s_1) \geq 2Rs(s_2)$ [7,8].

Intuitively, for any point p in A , p is assumed to be covered by a node s if their Euclidian distance is less than the sensing range of s , i.e. $d(ps) < Rs(s)$. Similarly, we define the convex region A as having a coverage degree of K if every location inside A is covered by at least K nodes. In this paper, we denote the coverage degree of p and A as $Cov(p)$ and $Cov(A)$.

2.2 Unnecessary Sensor Node

Based on the above model, we begin to discuss the characters of heterogeneous sensor network. The difference of the sensing radius of sensor nodes in heterogeneous sensor networks augments the computational difficulty of coverage degree. For example, consider the scenario illustrated by Figure 1, the sensing area of s_2 and s_3 is entirely enclosed by the sensing circle of s_1 .

The phenomena of "enclose" in heterogeneous sensor networks create a new kind of nodes which we call *Unnecessary Sensor Node, USN*. Before giving the definition of *USN*, we introduce several notions as follows.

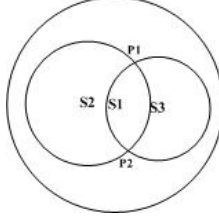


Fig. 1. Unnecessary Sensor Node

Definition 1: Region Point. The intersection or tangent point of the boundary of region A and the sensing circle of a sensor node, is called *Region Point*, denoted as RP .

Definition 2: Sensor Point. The intersection or tangent point of the sensing circles of two adjacent sensor nodes, is called *Sensor Point*, denoted as SP .

For a given node, there may exist two special kinds of points covered within its sensing area, defined as follows.

Definition 3: Circle Point. For any sensor $s \in S$, the *Region Point* or the *Sensor Point* on the sensing circle of s , is called *Circle Point*, denoted as CP .

Definition 4: Interior Point. For any sensor $s \in S$, the *Region Point* or the *Sensor Point* inside the sensing circle of s , is called *Interior Point*, denoted as IP .

In this paper, for any point p in region A , we define $Cro(p)$ as the number of the sensing circles that cross p . Generally, $Cro(p) = 2$ if p is a *Sensing Point* while $Cro(p) = 1$ if p is a *Region Point*. In some unusual cases, there may exist more than 2 circles crossing a point. Shown as Figure 1, point p_1 and p_2 are *Sensor Points*, they are the *Circle Points* of the nodes s_2 and s_3 ; Simultaneity, they are also the *Interior Points* of node s_1 . On the other hand, *Region Point* also can be the *Circle Point* or *Interior Point* of a certain node in the sensing region.

Now, let's define the notion of *USN*.

Definition 5: Unnecessary Sensor Node. For any sensor node $s \in S$, if s has no *Circle Point* on its sensing circle, we call s an *Unnecessary Sensor Node*, denoted as *USN*.

USN has no *Circle Point*, but may have *Interior Point*. The *Interior Points* of *USN* are the intersection or tangent points of the sensing circles enclosed by the circle of *USN*, we call them *Unnecessary Points*, UP . On the other hand, the intersection or tangent points in region A which are outside the circles of *USN* are called *Necessary Point*, NP .

Theorem 1: Whether the *Unnecessary Sensor Node* is active does not affect the coverage degree of the deployed region.

Proof: Intuitively, the coverage degree of the deployed region is the degree of the location in this region which is monitored by the smallest number of sensor nodes. Therefore, to prove the theorem, we should prove that the location with the lowest coverage degree is outside the sensing circle of *USN*.

We prove by contradiction. Illustrated by Figure 2(a), suppose s_i is an *USN*, p is the point that has the lowest coverage degree K in region A , p_1 is a randomly selected point on $C(s_i)$. Join pp_1 and extend it until it intersects the sensing circle of a node (denoted as s_j) at p_2 . Assume p_3 is a randomly selected point on p_1p_2 , there are two possible cases.

Case1: All the points including p_3 on p_1p_2 are outside $C(s_i)$. Clearly, $Cov(p_3)$ is smaller than $Cov(p)$ because the sensing area of s_i covers p , but does not cover p_3 .

Case2: All the points including p_3 on p_1p_2 are inside $C(s_j)$. Since s_i is an *USN*, $C(s_i)$ does not have any intersection with the rest nodes in region A , thus $C(s_j)$ must enclose $C(s_i)$, and the points p and p_3 are both inside the sensing area of s_j . Therefore, $Cov(p) > Cov(p_3)$ still holds.

From the proof of case 1 and case 2, we can come into the conclusion that p is not the point with the lowest coverage degree. This contradicts with the assumption, so the theorem is proved.

Theorem 2: Whether the node whose sensing circle is enclosed by the sensing circle of an *USN* is active doesn't affect the coverage degree of the deployed region.

Proof: Illustrated by Figure 2(b), similar to the proof of theorem 1, it is easy to prove that the point having the lowest coverage degree doesn't lie in the sensing area of node s_j whose sensing circle is enclosed by the sensing circle of s_i , an *Unnecessary Sensor Node*.

Theorem 3: All the *Region Points* are *Necessary Points*.

Proof: Illustrated by Figure 2(c), suppose rp_1 is a *Region Point* of node s_i and region A . For any node whose sensing area covers rp_1 , such as s_j , since the length of segment s_jrp_1 is not longer than $Rs(s_j)$, i.e. $d(s_jrp_1) \leq Rs(s_j)$, s_j must intersect region A . Therefore, s_j is not an *USN*, and rp_1 is not covered by any *USN*. rp_1 is a *Necessary Point*.

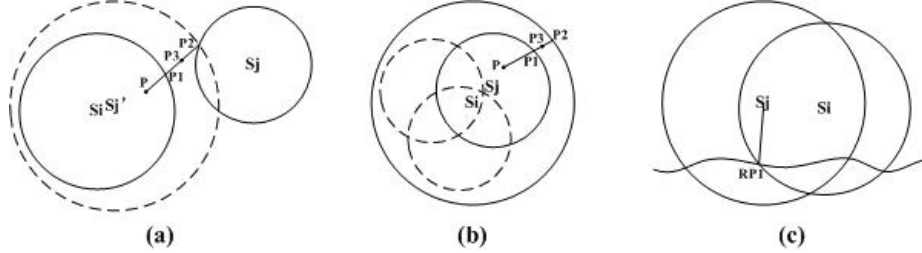


Fig. 2. Samples of Theorems about Unnecessary Sensor Node

Based on Theorem 3, only the *Sensor Points* in the deployed region are likely to be *USN*, thus we sort them into *Necessary Sensor Points* and *Unnecessary Sensor Points*.

3 Coverage Guarantee of Heterogeneous Sensor Networks

For a heterogeneous sensor network, it is important to find out whether the deployed region achieves the expected coverage degree. Obviously it is impossible to calculate the coverage degree of every location in the deployed region. Some papers [1, 5, 6, 7] have dealt with this problem, however, their strategies can not be applied to heterogeneous sensor networks. Based on the analysis of heterogeneous sensor network in previous paragraph, we propose a *Coverage Guarantee Theorem*.

Theorem 4: Suppose convex region A is deployed by a heterogeneous sensor network, A is K -covered if and only if all of the following conditions are satisfied:

Condition 1: There exist *Region Points* in region A

Condition 2: There exist *Necessary Sensor Points* in region A

Condition 3: For any *Region Point* rp in A , $Cov(rp) - Cro(rp) \geq K$

Condition 4: For any *Necessary Sensor Point* sp in A , $Cov(sp) - Cro(sp) \geq K$

Proof: Firstly, we try to prove the if part, i.e. prove that if region A is K -covered, the four conditions must be satisfied.

Condition 1: As illustrated in Figure 3(a), let p be any point on the boundary of region A , since A has a coverage degree of K , p is monitored by at least K sensors. Let node s be any of the sensors covering p , since $d(sp) \leq Rs(s)$, s must have intersection or tangent points with the boundary of A , thus there exist *Region Points* in region A .

Condition 2: We prove by contradiction, suppose there is no *Necessary Sensor Point* in region A . As illustrated in Figure 3(b-1) and (b-2), let s_i be the node that has the largest sensing radius; let s_j be the node whose circle is closest to the circle of s_i , i.e., for any $s \in S$, $d(s_i s_j) - Rs(s_i) - Rs(s_j) \leq d(s_i s) - Rs(s_i) - Rs(s)$. Join s_i and s_j , suppose p_1 is the intersection point of the segment $s_i s_j$ and $C(s_i)$, and p_2 is the intersection of segment $s_i s_j$ and $C(s_j)$. Let p be a randomly selected point on $p_1 p_2$, since A has a coverage degree of K , p is monitored by at least K sensors. Let node s_k be any of the sensors covering p , Join s_i and s_k , suppose the line which joins s_i and s_k intersects two sensing circles at points p_3 and p_4 respectively. Draw a line tangent to $C(s_k)$ at point p_4 which intersects the segment $s_i s_j$ at point p_5 . There are two possible cases: the sensing area of s_j is outside $C(s_k)$ (illustrated by Figure 3(b-1)) or inside $C(s_k)$ (illustrated by Figure 3(b-2)). In both cases, it is obvious that the length of right-angle side $s_i p_4$ is shorter than the length of slope side $s_i p_5$ in right triangle $s_i p_4 p_5$, thus $d(p_3 p_4) < d(p_1 p_3) < d(p_1 p_2)$. This implies that $C(s_k)$ is closer to $C(s_i)$ than $C(s_j)$, which contradicts with the assumption. Therefore s_k is inexistent. From the above analysis, we can draw the conclusion that the sensing circles of nodes s_i and s_j must have intersection or tangent points. Since $C(s_i)$ is the largest circle in region A , there exist *Sensor Points* in region A .

Condition 3: As illustrated in Figure 3(c), suppose rp_1 is any *Region Point* which is created by $C(s_i)$ and $Bond(A)$. Outside the sensing area of s_i , let rp_2 be the *Region Point* that has the shortest path to rp_1 along $Bond(A)$. There are two possible cases: rp_1 is outside $C(s_j)$ or inside $C(s_j)$. Suppose p is a randomly selected point on path $rp_1 rp_2$, in both case1 and case2, it is obvious that all points on path $rp_1 rp_2$ have the same coverage degree, thus $Cov(rp_1) - Cro(rp_1) = Cov(p)$. Since A has a coverage degree of K , p is monitored by at least K sensors. Therefore, $Cov(rp_1) - Cro(rp_1) = Cov(p) \geq K$.

Condition 4: Suppose sp_1 is any *Necessary Sensor Point* which is created by $C(s_i)$ and $C(s_j)$. Join $sp_2 sp_1$ and extend it until it intersects a sensing circle (As illustrated in Figure 3(d-1)) or $Bond(A)$ (As illustrated in Figure 3(d-2)) at point p_1 . Similar to the proof of condition 3, all points on segment $p_1 sp_1$ have the same coverage degree, thus it is easy to prove that for any point p on the segment $p_1 sp_1$, $Cov(sp_1) - Cro(sp_1) = Cov(p) \geq K$.

Therefore, the if part is proved.

Then, we try to prove the only if part, i.e. prove that region A must be K -covered, if the four conditions are satisfied.

To prove that A is K -covered, we should prove that all the points in A are K -covered. We split our consideration into two cases. In case 1, we discuss the points inside $Bond(A)$, in case 2, we discuss the points on $Bond(A)$.

Case1: As illustrated in Figure 4(a), suppose p is any point inside $Bond(A)$. Based on *Condition 2*, there exists *Necessary Sensor Point* in region A . Let sp_1 be the closest *Necessary Sensor Point* to p , i.e., for any sp in region A , $d(psp_1) \leq d(psp)$. Join psp_1 ,

suppose p_1 is the closest intersection point to p on the segment psp_1 , which is created by the intersection of psp_1 and the sensing circle of a node (denoted as s_k). If s_k is an *USN*, turn it off (by *Theorem 1*) and continue to search the closest intersection point to p on psp_1 , until the closest intersection of psp_1 and the sensing circle of a *non-USN* is found. If this intersection is sp_1 , since all points on segment psp_1 have the same coverage degree, $Cov(p) = Cov(sp_1) - Cro(sp_1)$. Based on *Condition 4*, $Cov(sp_1) - Cro(sp_1) \geq K$, thus $Cov(p) \geq K$. If this intersection is not sp_1 , denote it as p_m , suppose it is created by the intersection of segment psp_1 and the circle of *non-USN s_m . Assume sp_2 is the closest *Sensor Point* to p_m along $C(s_m)$. Since all the points on segment pp_m have the same coverage degree and at the same time, all the points on arc p_msp_2 have the same coverage degree, thus based on *Condition 4*, $Cov(p) = Cov(p_m) - Cro(p_m) = Cov(sp_2) - Cro(sp_2) \geq K$.*

Case 2: As illustrated in Figure 4(b), suppose p is any point on $Bond(A)$, Based on *Condition 1*, let rp_1 be the *Region Point* that has the shortest path to p along $Bond(A)$. If p is located outside $C(s_i)$, then $Cov(p) = Cov(rp_1) - Cro(rp_1)$; If p is located inside $C(s_i)$, $Cov(p) > Cov(rp_1) - Cro(rp_1)$. Based on *Condition 3*, $Cov(rp_1) - Cro(rp_1) \geq K$, thus $Cov(p) \geq K$.

Therefore, the only if part is proved. Now we can draw the conclusion that the theorem is true.

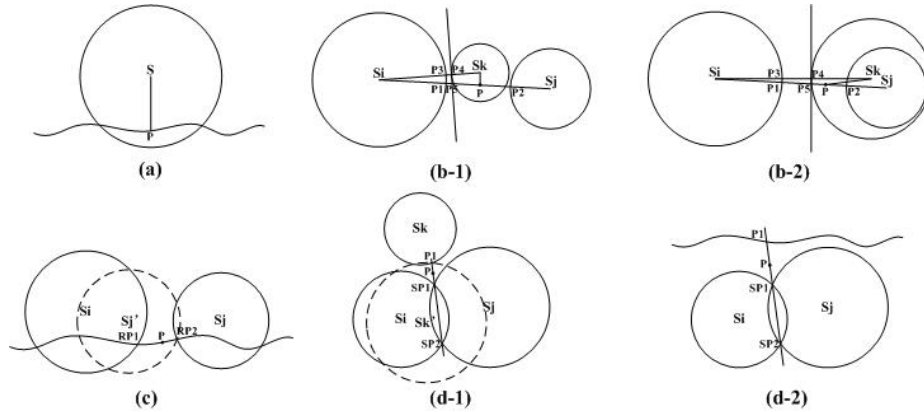


Fig. 3. Proofs of the if part

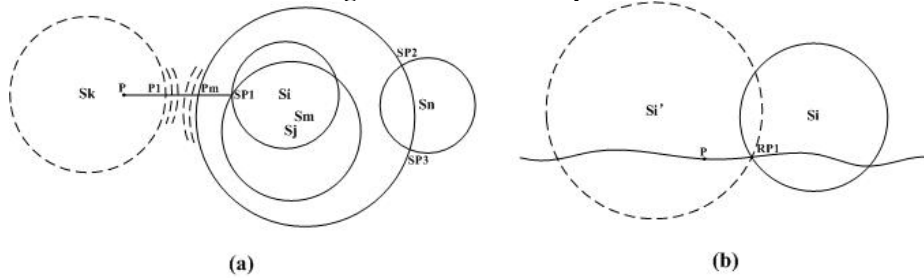


Fig. 4. Proofs of the only if part

Based on the *Coverage Guarantee Theorem* of heterogeneous sensor network, a conclusion can be drawn that for any *Region Point* or *Sensor Point* p in the deployed region, if the value of $Cov(p) - Cro(p)$ is not lower than the given coverage degree,

the coverage of this region is guaranteed. Therefore, for a convex region A , the coverage degree of A can be calculated by the following formula.

$$Cov(A) = \min(\min(Cov(RP) - Cro(RP)), \min(Cov(SP) - Cro(SP))) \quad (1)$$

4 Distributed Coverage Optimization Algorithm

4.1 Coverage Calculation of Sensor Node

If we regard the sensing area of a sensor node s as the deployed region, then the *Circle Point* of s can be considered as the *Region Point* of this circle region, and the *Interior Point* of s can be considered as the *Sensor Point*. Based on the *Coverage Calculation Formula* for the deployed region, we can derive a formula to calculate the coverage degree of s .

$$Cov(S) = \min(\min(Cov(CP) - Cro(CP)+1), \min(Cov(IP) - Cro(IP))) \quad (2)$$

Different from *Formula (1)*, we should add 1 to the value of $Cov(CP) - Cro(CP)$ because the bound of this region, i.e., the sensing circle of s , is included in the count of $Cro(CP)$.

4.2 Design and Analysis of Algorithm

Based on *Formula (2)*, to determine whether a node s should be turn active/inactive, we must find all the *Circle Points* and *Interior Points* of this node. Therefore, all the nodes having intersecting sensing area with s should be considered. We call such nodes the *Neighbor Nodes* of s , which compose the *Neighbor Set* of s .

Definition 6: *Neighbor Set.* Suppose node $s \in S$, for any other node $s_i \in S$, if $d(ss_i) \leq Rs(s) + Rs(s_i)$, then $s_i \in NS(s)$.

Now we introduce the *Distributed Coverage Optimization Algorithm*. For any given node s , the input is the expected coverage degree K and the output is a Boolean Variable $s.active$ which denotes whether s should be turn active/inactive.

```

Procedure Coverage Optimization( $s, K$ )
/* Search Neighbor Sensors */
1: for any  $s_i \in S$  do
2:   if  $d(ss_i) \leq Rs(s) + Rs(s_i)$ 
3:     then  $NS(s) \leftarrow s_i$ ; end if end for
/* Search Region Points of  $s$  and put them into Circle Point Set */
4:  $CP(s) \leftarrow \{p \mid p \in \text{the intersection or tangent points of } s \text{ and } A\}$ ;
/* Neighbor Set */
5:  $n \leftarrow NS(s).length$ ;
6: for  $i \leftarrow 1$  to  $n$  do
/* Search Sensor Points of  $s$  and put them into Circle Point Set */

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7: if  $d(sns_i) \geq |Rs(s) - Rs(ns_i)|$ 
8:   then  $CP(s) \leftarrow \{p \mid p \in \text{the intersection or tangent points of } s \text{ and } ns_i\}$ ;
9: end if
/* Search Region Points of Neighbor Sensors and put them into Interior Point Set */
10:  $IP(s) \leftarrow \{p \mid p \in \text{the intersection or tangent points of } ns_i \text{ and } A$ 
       $\&\& d(sp) \leq Rs(s)\}$ ;
/* Search Sensor Points of Neighbor Sensors and put them into Interior Point Set */
11: for  $j \leftarrow i$  to  $n$  do
12:   if  $d(ns_i, ns_j) \leq Rs(ns_i) + Rs(ns_j)$   $\&\& d(ns_i, ns_j) \geq |Rs(ns_i) - Rs(ns_j)|$ 
13:     then  $IP(s) \leftarrow \{p \mid p \in \text{the intersection or tangent points of } ns_i \text{ and } ns_j$ 
           $\&\& d(sp) \leq Rs(s)\}$ ;
14:   end if end for end for
/* Calculate minimal coverage degree of Circle Points of  $s$  */
15:  $m \leftarrow CP(s).length$ ;
16:  $int\ minCP \leftarrow \infty$ ; //initialize the minimal coverage degree with a large value
17: for  $i \leftarrow 1$  to  $m$  do
18:    $Cov(cp_i) \leftarrow 1$ ; // $cp_i$  is at least covered by  $s$ 
19:   for  $j \leftarrow 1$  to  $n$  do
20:     if  $d(cp_i, ns_j) < Rs(ns_j)$  //subtract  $Cro(cp_i)$  from  $Cov(cp_i)$  by excluding the case of "="
21:       then  $Cov(cp_i)++$ ; end if end for
22:   if  $Cov(cp_i) < minCP$ 
23:     then  $minCP \leftarrow Cov(cp_i)$ ; end if ed for
/* Calculate minimal coverage degree of Interior Points of  $s$  */
24:  $m \leftarrow IP(s).length$ ;
25:  $int\ minIP \leftarrow \infty$ ; //initialize the minimal coverage degree with a large value
26: for  $i \leftarrow 1$  to  $m$  do
27:    $Cov(ip_i) \leftarrow 1$ ; // $ip_i$  is at least covered by  $s$ 
28:   for  $j \leftarrow 1$  to  $n$  do
29:     if  $d(ip_i, ns_j) < Rs(ns_j)$  //subtract  $Cro(ip_i)$  from  $Cov(ip_i)$  by excluding the case of "="
30:       then  $Cov(ip_i)++$ ; end if end for
31:   if  $Cov(ip_i) < minIP$ 
32:     then  $minIP \leftarrow Cov(ip_i)$ ; end if end for
/* Calculate coverage degree of  $s$  */
33: if  $minCP > minIP$ 
34:   then  $Cov(s) \leftarrow minIP$ ;
35: else  $Cov(s) \leftarrow minCP$ ; end if
/* whether  $s$  is an Unnecessary Sensor Node */
36: if  $|CP(s)| = 0$ ;
37:   then  $s.active \leftarrow false$ ;
38: else  $s.active \leftarrow true$ ; end if
/* whether the coverage degree of  $s$  is higher than expected */
39: if  $Cov(s) > K$ ;
40:   then  $s.active \leftarrow false$ ;
41: else  $s.active \leftarrow true$ ; end if
/* return the optimization result that  $s$  should be turned active/inactive */

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42: return s.active;
```

5 Experimentation

In this section, we evaluate the *Distributed Coverage Optimization Algorithm* by simulation experiments. Suppose the test region is a $100m \times 100m$ rectangular area, and we deploy three homogeneous sensor networks and one heterogeneous sensor network in the test region separately. Suppose the sensing radiuses of sensor nodes in three homogeneous sensor networks are $20m$, $25m$ and $30m$ respectively, and the heterogeneous sensor network is composed of same number of these three types of nodes.

We investigate the performances of coverage optimization using *DCOA* for these four sensor networks, and all the results in this section are based on at least five runs with different random network topologies.

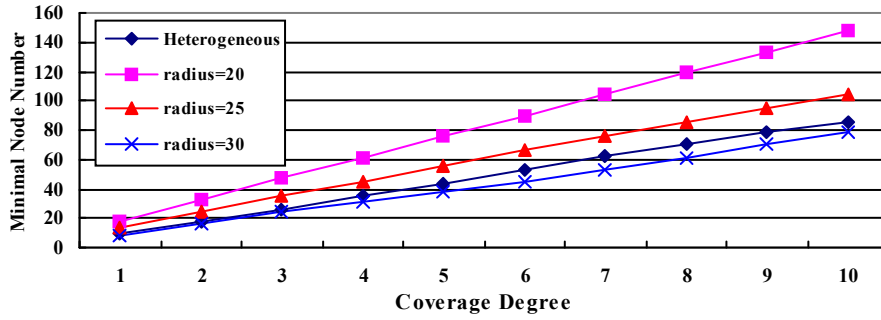


Fig. 5. The minimal numbers of nodes need to remain active

As illustrated in Figure 5, in homogeneous sensor networks, for any expected coverage degree from 1 to 10, the minimal number of nodes that need to be deployed reduces with the increase of sensing radius. For the heterogeneous sensor network, the minimal number of nodes needs to be deployed in the test region is between the 25m-homogeneous sensor networks and the 30m-homogeneous sensor network.

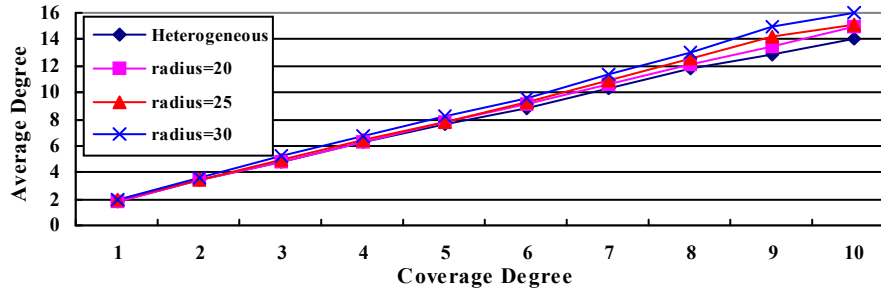


Fig. 6. The average degree of the deployed region

As illustrated in Figure 6, in homogeneous sensor networks, for any expected coverage degree from 1 to 10, the average coverage degree in the test region increases

with the augment of sensing radius. For the heterogeneous sensor network, the average coverage degree in the test region is lower than any of the three homogeneous sensor networks.

7 Conclusion

In this paper, we explore the problem of coverage in wireless sensor networks. Different from the previous schemes, the algorithm and protocol presented in this paper can be applied to not only homogeneous sensor networks, but also heterogeneous sensor networks. In heterogeneous sensor networks, the difference of sensing radius of sensor nodes should be taken into account because this difference can create *Unnecessary Sensor Nodes* which have no intersection or tangent points with the sensing circle of other nodes. The *Distributed Coverage Optimization Algorithm* proposed in this paper is a good solution for this problem. It can turnoff the abundant nodes including *Unnecessary Sensor Nodes* as well as guarantee the expected coverage degree of the deployed region.

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