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무선 센서 네트워크에서 유효 커버리지 및 접속성 보장을 위한 중앙 집중형 배치 프로토콜*

A Centralized Deployment Protocol with Sufficient Coverage and Connectivity Guarantee for WSNs

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요 약

무선 센서 네트워크에서 에너지 소비의 효율성은 전체 네트워크 수명 시간을 결정하기 때문에 에너지 소비를 최소화하기 위한 연구가 활발히 진행되고 있다. 무선 센서 네트워크에서 에너지 보전을 위해서는 운영에 필요한 최소한 센서 노드만을 활성화된 상태로 유지하고 나머지 노드들은 휴면 상태로 유지하여 불필요한 에너지 소비가 일어나지 않도록 하여야 한다. 그러나 얼마만큼의 센서 노드들을 최적의 운영 노드 집합에 포함시킬 것인지를 계산하는 것은 NP-hard 문제로 알려져 있다. 본 논문에서는 최적에 근접한 커버 집합(cover set)을 생성하기 위하여 CVT 기반의 근사화 알고리즘을 제안하였다. 제안된 알고리즘에서는 센서의 통신 범위가 센싱 범위의 두 배 이상이면 커버 집합에 속한 센서 노드 간의 연결이 즉시 이루어지도록 하고 반면에 통신 범위가 센싱 범위의 두 배 이하이면 커버 집합의 접속성 보장을 위하여 보조 노드를 결정하는 연결 기법을 제시하였다. 마지막으로 제안된 알고리즘의 성능 평가를 위하여 이론적 분석과 실험을 수행하였으며, 실험결과를 통해 제안된 알고리즘이 Greedy 알고리즘보다 CCS(Connected Cover Set)의 크기와 실행 시간 측면에서 우수함을 보였다.

Abstract

Reducing power consumption to extend network lifetime is one of the most important challenges in designing wireless sensor networks. One promising approach to conserving system energy is to keep only a minimal number of sensors active and put others into low-powered sleep mode, while the active sensors can maintain a connected cover set for the target area. The problem of computing such minimum working sensor set is NP-hard. In this paper, a centralized Voronoi tessellation (CVT) based approximate algorithm is proposed to construct the near optimal cover set. When sensor's communication radius is at least twice of its sensing radius, the cover set is connected at the same time; In case of sensor's communication radius is smaller than twice of its sensing radius, a connection scheme is proposed to calculate the assistant nodes needed for constructing the connectivity of the cover set. Finally, the performance of the proposed algorithm is evaluated through theoretical analysis and extensive numerical experiments. Experimental results show that the proposed algorithm outperforms the greedy algorithm in terms of the runtime and the size of the constructed connected cover set.

Key Words : CVT, MIS, MCCS, Connectivity, Coverage, NP-hard

I. Introduction

A wireless sensor network consists of a large number of sensor nodes that perform sensing, computation, and communication. It has become an attractive modern tool for surveillance and protection applications, such as museum monitoring, military surveillance, object track-ing, and intrusion detection. For limitation of volume and cost, the sensor nodes are generally equipped with capacity-limited battery, further more, the density of the sensor nodes in the network is too large or the sensor network is usually deployed in battlefield, desert or other dangerous environment, sensor replacement or battery recharge is impossible. On the other hand, we expect the lifetime of the sensor networks as long as possible. How to prolong the lifetime of the entire network with the low power and short lifetime of sensors is a main challenge in designing wireless sensor networks.

Density control is an effective and efficient approach to realize the above object. Here density control means putting some nodes into low-power sleeping status, only

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keeping part of the nodes active while satisfying the performance requirement. In order to keep the original system performance, density control must hold the following two conditions: (1) guarantee the full coverage of the target area, (2) guarantee the connectivity of the communication network.

This paper discusses how to choose the minimal number of active sensors satisfying the coverage and connectivity requirement for the initial network deployment. For a given target area, it is NP-hard problem. To handle the problem mentioned above, we propose a centralized polynomial approximate algorithm. The basic idea is that: computing the near optimal cover set first. If the transmission range of the sensor nodes is more than or equal to two times of the sensing range, the cover set is connected at the same time; when the transmission range is less than two times of the sensing range, the connectivity of the cover set can not be guaranteed. With the basic idea, we design an algorithm based on the calculation of shortest-path(SP) between two points to calculate the additional nodes needed for constructing the connectivity of the cover set.

The rest of the paper is organized as follows: Section II focuses on related contributions to date and analyses their advantages as well as disadvantages, and it points out the main research directions. Section III is the system model considerations, which describes the problem we try to deal with and explains some theories we will use in the paper. Section IV is the main part. The CVT-A* algorithm is described. Finally, in Section V, it gives the results of performance evaluation, where it proves the superior of CVT-A* to the greedy algorithm through experiment data as well as theoretical analysis. Future works and conclusions in Section VI give a brief sum- mary of the dissertation as well as the future works needed to enhance our contribution for the better use.

II. Related Works

Although the approach that achieving energy conservation by scheduling nodes to sleep is not a new one, none of the existing protocols satisfy the complete set of requirements in sensor networks. First, most existing solutions have treated the problems of sensing coverage and network connectivity separately. Up to now, the problem of sensing has been extensively investigated. Several algorithms aim to find a near optimal solution based on global information. Meguerdichian [2] applies linear programming techniques to select the minimal set of active nodes for maintaining coverage. Slijepcevis [3] discusses how to prolong the network lifetime making use of the cover redundancy of sensor nodes. Chen [4] proposes a node selection approach based on grid plot. None of the above coverage maintenance protocols addresses the problem of maintaining network connectivity. On the other hand, several other protocols (e.g., ASCENT [5], SPAN [6]) aim to maintain network connectivity but do not guarantee sensing coverage. Unfortunately, satisfying coverage or connectivity alone is not sufficient for a sensor networks to provide adequate service.

III. System Model Considerations

3.1 Problem Formulation

Given planar R^2 , the sensing range of sensor s_i is defined as the circular disk with centre s_i and radius R_s, where R_s is the sensing radius. We represent it like this: $\{S_i = p_i | p_i \in R^2 d(p_i, s_i) \leq R_s\}$, here, $d(p_i, s_i)$ is the Euclidean distance. The entire coverage range of a sensor network C is the sum of the sensing range of all sensors, i.e. $C = \sum_{i=1}^{n} S_i$. If P is covered by sensor s_i , there is $d(P, s_i) \leq R_s$. It holds that if the target area R is full covered by a sensor network, each point in R is covered by at least one sensor. The direct communication range for sensor s_i is the circular with centre s_i and radius R_c.. Each sensor can only communicate directly with sensors within the range.

Definition 1. Given a sensor nodes set S, the communication graph $G_c = (V_c, E_c)$, composed of the sensor nodes in S , is an undirected graph. $V_c = S$, $\forall s_i, s_j \in S$, $(s_i, s_j) \in E_c$, $(d(s_i, s_j) \leq R_c)$ [9].

We say communication graph G_c is induced from set S . The communication path $p = \{s_1, s_2, s_3 \ldots\}$ is a sequence of sensors and each pair next to each other are communication neighbours. For communication graph G_c, if there is a communication path between any two sensors, we say it is connected.

Definition 2. Given a sensor nodes set S and a target area R , if each sensor in R is covered by at least one sensor in S, then S is a cover set of R . And if at the same time the communication graph induced from the set S is connected, we mark set S be the connected cover set of R , i.e. the CCS of R [9].

3.2 Brief Overview of Voronoi Tessellation and Delaunary Triangulation

Given a set S of n sites $\{s_1, s_2, s_3 \ldots\}$in the plane, the Voronoi diagram is defined as the subdivision of the plane into n cells, one for each site, with the property that any point in the cell corresponding to a site is closer to that site than to any other site. Formally, the cell corresponding to site s_i is defined as:

$$Cell_{VT}(s_i) = \{x \mid dist(s_i, x) \le dist(s_j, x)\}$$

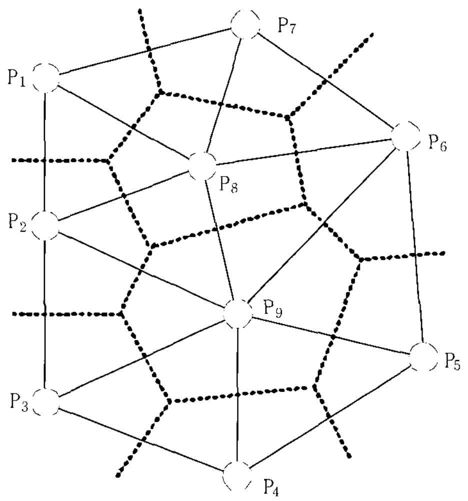

Fig 1. Voronoi and Delaunary diagram for 9 points

Two Voronoi vertexes share a Voronoi edge and three Voronoi cells intersect at a Voronoi vertex.

If all sites are not in the same line and there are two cells $cell(p_i)$, $cell(p_j)$, share one edge, link the two sites. Repeat the process for the n sites; we can get the unique grid connecting the n sites, i.e. the Delaunary Triangulation, the dual of Voronoi Tessellation. In Figure 1, the dashed line is the Voronoi Tessellation for the 9 points while the real line shows the Delaunary Triangulation.

IV. CVT-A^* Algorithm

4.1 The Relationship of Coverage and Connectivity

If $R_c \ge 2R_s$, two sensors whose sensing region have intersection can communicate directly with each other.

Prove: consider two sensors s_i, s_j with sensing radius R_s. There are three relationships between two disks: intersect, tangent and separate. The largest distance between two centers of circles with intersections is two times of the radius when the two have only one inter-section point, i.e. $d(s_i,s_j) \le 2R_s$, so it hold $d(s_i,s_j) \le 2R_s \le R_c$, we can say s_i, s_j can communicate with each other directly.

Definitely, when $R_c < 2R_s$, we can not guarantee that two sensors with sensing intersection can communicate directly.

4.2 CVT Algorithm

It aims to construct the near optimal cover set. The basic idea is: distinguish the candidate turn-off nodes in the network; calculate the candidate turn-off nodes that can be turned off simultaneously. Then the active working nodes form the cover set for the target area.

4.2.1 Distinguish the Candidate Turn-off Nodes

Definition 3. One sensor is called a candidate turn-off sensor node if its sensing region is completely covered by other sensors.

Definition 4. The point (or point set) in the target area is said to be a sensing hole if it is not covered by any node.

Let's consider a sensor network $S = \{s_1, s_2, s_3 \ldots\}$ deployed in a bounded convex region R. Take the sen- sor nodes as the generation points; we get the unique Voronoi tessellation of R. Each $cell_{VT}s_i$ on planar is a convex polygon.

In this paper follows, we use $BVT(S,R)$ to denote the bounded Voronoi tessellation for area R S is the Voronoi generation points set; $BVP_i(S,R)$ denotes the bounded Voronoi polygon associated with node s_i; $BVV_i(S,R)$ presents the Voronoi vertex for sensor s_i; $BVN_i(S,R)$ stands for the Voronoi neighbours of s_i.

In bounded Voronoi tessellation, the Voronoi polygons are all convex polygons. So it holds: a convex polygon is covered by a circle is equal to each vertex of the Voronoi polygon is inside the circle.

Lemma 1. If $BVP_i(S,R)$ of sensor s_i is full covered by the sensing disk S_i, it is equivalent to all the $BVV_i(S,R)$ are inside S_i.

In other words, $\forall v_i \in BVV_i(S,R)$, $d(v_i,s_i) \le R_s$, the Voronoi polygon $BVP_i(S,R)$ is covered by sensor s_i.

Theorem 1. Bounded convex region R is full covered by a sensor network S is equivalent to the sensing disk of each sensor covers all the vertexes of the associated bounded Voronoi polygon.

Theorem 1 gives us a method to estimate whether a sensor set S is a cover set of area R or not.

If turning off sensor $s_i \in S$ can not introduce sensing holes, it equals to set $SRSLANTs_i$ ($SRSLANTs_i$ denotes the sensor set S without sensor s_i) remains to be a cover set for region R it also means that for any node $s_j \in SRSLANTs_i$, $BVP_j(S,R)$ of $BVT(SRSLANTs_i,R)$ is covered by s_j. We can figure out the following reality through further observation: only $BVP_j(S,R)$,

$s_j \in BVN_i(S,R)$ will be changed, the bounded Voronoi polygon of other sensors will not be changed between the two Voronoi tessellations, it is because that $BVP_j(S,R)$ should be covered by its Voronoi neighbours.

Definition 5. Node s_i is a candidate turn-off node is equivalent to:

$$\forall v_j \in BVN_i(S,R),\ BVP_j(SRSLANTs_i, R) \subseteq S_j.$$

4.2.2 Ascertaining Active Working Nodes

Definition 6. For one candidate turn-off node, if at least one of its Voronoi neighbours is a candidate turn-off sensor node, we denote the node as a pending turn-off sensor node; if all its Voronoi neighbours are not candidate turn-off sensor nodes, we name it an absolute turn-off sensor node.

Definition 7. $PTG(V,E)$ is an undirected graph, where V is the set of all the pending turn-off nodes in the network. $\forall v_i, v_j \in V$, $(v_i, v_j) \in E$ is equivalent to v_i and v_j are Voronoi neighbours. The dependency degree of a pending turn-off sensor node is the edge number linked to this node in *PTG*..

PTG is the subgraph of Delaunary triangulation. We can get the *PTG* graph through deleting all the non-candidate turn-off sensor nodes, the absolute turn-off sensor nodes as well as the associated edges from the Delaunary triangulation $G_D = (V_D, E_D)$.

Calculating the number of the pending turn-off sensor nodes that can be turned off simultaneously is equivalent to calculating the maximum independent set (*MIS*) of *PTG*, which is also NP-hard. We adopt an algorithm similar to the greedy algorithm described in [7], to find the pending turn-off sensor nodes that can be turned off simultaneously. It works as follows: select the sensor with the lowest dependency degree in *PTG* (if two sensors that sharing the same Delaunary edge have the same dependency degree, we choose either of them randomly), put it into set Q, and then delete this sensor, all the neighbour sensors as well as the associated edges of all these sensors. Repeat the above process until *PTG* is empty. When the algorithm comes to the end, we get set Q, the *MIS* of *PTG*. Figure 2 shows how to construct the *PTG* as well as the *MIS* of a *PTG*. a) is a sensor network; b) shows the *PTG* of a); we get b) by deleting all the WS (working sensor), ATS (absolute turn-off sensor) and the edges link to them in a). In b), sensor A, E, F, G, H have the lowest pending degree 1, here, we choose A, E, G to set Q, and delete the corresponding edges link to them. Then we get c), assuming we choose C to set Q. Now the *PTG* is empty, Q= {A, E, G, C}, which is the *MIS* of a).

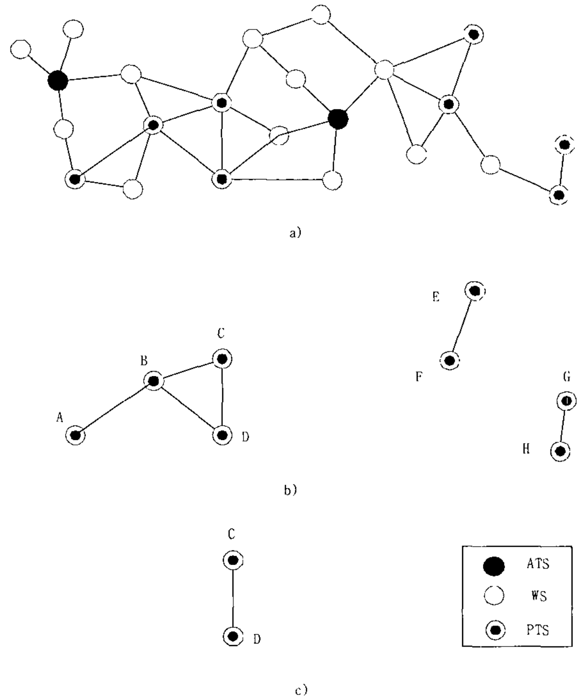

Fig 2. *PTG* of a sensor network & its *MIS*

The pending turn-off nodes selected in the *MIS* of *PTG* can be safely turned off while other pending turn-off nodes must be active.

<u>Algorithm: CVT</u>

Input: initial sensor set $IS = \{s_1, s_2 ... s_n\}$, target area R.

Output: the cover CS set of area R.

// Notation: ATS: the absolute turn-off sensor set PTS: // Pending turn-off sensor set; SS: safe sensor set;

//MIS: maximum independent set;

// S: temporal sensor set.

Step 1. $SS = CS = \emptyset$, $S = IS$

Step 2. Calculate the bounded Voronoi tessellation $BVT(S,R)$ for area R.

Step 3.

While ($S \neq \emptyset$)

Step 3.1 $ATS = PTS = MIS = \emptyset$

Step 3.2 Distinguish the candidate turn-off nodes in S

Step 3.3 Sort the candidate turn-off nodes

For each candidate turn-off node $s_i \in S$

If (s_i is an absolute turn-off node) Then

$ATS = ATS \cup \{s_i\}$

Else $PTS = PTS \cup \{s_i\}$

End For;

Step 3.4

If ($PTS \neq \emptyset$) Then

Calculate the *MIS* of *PTG*

$SS = SS \cup ATS \cup MIS$
$S = IS - SS$
Else
$SS = SS \cup ATS$
End While
Step 4. Return $CS = IS - SS$

4.3 Algorithm Analysis

As we mentioned in section 4.1, when $R_c \geq 2R_s$, the cover set is connected at the same time.

The approximate performance of the CVT algorithm depends on the greedy algorithm calculating the MIS of a graph. For any graph with n vertexes, m edges, and average sensor degree δ, we can get a maximum independent set with the smallest size of $n/(\delta+1)$ within steps of $O(m)$ by greedy algorithm [8].

Lemma 2. In Voronoi tessellation for a planar, the Voronoi vertex number is less than or equal to $2n-5$, where n is the sensor number [8].

Lemma 3. The average edge number of the Voronoi polygon is no more than 6 [8].

Lemma 4. Constructing the planar Voronoi Tessellation for n generation points, the worst time complexity for planar scanning is $O(nlogn)$, the average time complexity is $O(n)$ [8].

Theorem 2. The worst time complexity of our algorithm is no more than $O(n^2 llogn)$, the average time complexity is no more than $O(n^2 l)$. Here l is the largest repetition time in Step 3 of our algorithm.

4.4 The Connectivity Scheme when $R_c < 2R_s$

According to 4.1, we can not guarantee the connectivity of the cover set calculated through CVT algorithm when $R_c < 2R_s$. We propose a connectivity scheme based on the CVT algorithm to calculate the assistant nodes needed for the connectivity of the cover set. During the calculation of the cover set described above, each sensor s_i in the cover set keeps a record of its coverage neighbors CN_i, and then one sensor can choose the sensors that need to be active to connect this sensor to all of its coverage neighbors using A^* algorithm.

To activate the smallest number of sensors, we use the hop count to determine the heuristic parameter $h(s_n)$ and parameter $g(s_n)$ in A^* algorithm. For two sensors with distance d, the smallest number of assistant nodes is $2d/R_c - 1$, which we can use to calculate $h(s_n)$ and $g(s_n)$ during the path finding.

For sensor s_i in the cover set calculated through CVT algorithm, it keeps one Link State parameter L_{ij} for each sensing neighbor to denote whether there is a communication path between it and its neighbor s_j. L_{ij} is true means there is a communication path between sensor s_i and sensor s_j; L_{ij} is false means there is no communication path between s_i and s_j. A sensor in the cover set will check all the Link State parameters and will run A* algorithm to calculate the assistant nodes if the Link State parameter is false. The following is the communication algorithm:

```
If (s_i ∈ CS) Then
  While (CN_i is not empty)
    For (s_j ∈ CN_i )
      If (!L_ij) Then
        Run A* algorithm to calculate the assistant
        nodes
        CN_i = CN_i\s_j
        L_ij = true
      End If
    End For
End If
```

Repeat the above process until all the sensors in the cover set can communicate with all of its sensing neighbors.

V. Performance Evaluation

In our experiment, the target area is a 400×400 rec-tangle area. The default value of R_s is 30. We change the value of R_c to realize different ratio of R_c/R_s, so as to evaluate the performance of our algorithm in different environments. The main performance metric is the size of the connected cover set (CCS). The smaller of the CCS, the less the total energy consumed is. To guarantee the full cover of the target area of the initial deployed sensors and form a connected communication network, we partition the target area to grid with side length 40, and deploy one sensor on the centre of each grid. Under such deployment, the smallest R_c for net-work connectivity is 40. When R_s is 30, the sensor in the center of the grid can cover the whole grid, so the initially deployed 100 sensors construct a connected cover set. Besides these 100 fixing deployed sensors, there are a large number of randomly deployed sensors for each topology during the simulation experiments.

5.1 Compare with the Greedy Algorithm

Gupta [1] proposes the centralized greedy algorithm for MCCS. It takes grid as the target area approximately, and partitions the grid into many sub area, each sub-area is covered by the same set of sensors. The biggest number of sub area formed by n circles on planar is $n(n-1)+1$ [1]. If put k sampling points into different sub-area, the time complexity of the preprocess for producing sub-areas is $O(kn^3)$ [4]. The time complexity of the greedy algorithm depends on the pre-processing process of sub area partition, so its time complexity is bigger than ours.

Table 1 shows the pre-processing time of the greedy algorithm with different sensor density and different size of the grid. Table 2 shows the runtime of CVT-A^* algorithm with different sensor density. From the above two tales, CVT-A^* is obviously superior to the greedy algorithm in runtime.

Table 1. Pre-processing time of Greedy Algorithm

Grid Size	R_s	Node Number	Pre-processing Time
0.1	30	200	>1hour
0.1	30	300	>1hour
0.1	30	400	>1hour
0.5	30	200	33.2s
0.5	30	300	160.3s
0.5	30	400	900.1s
1	30	200	7.9s
1	30	300	50.3s
1	30	400	240.2s

Table 2. Runtime of CVT-A^* algorithm

R_c	Node Number	Runtime
40	200	1.65s
40	300	3.60s
40	400	6.01s
60	200	1.75s
60	300	4.50s
60	400	7.82s

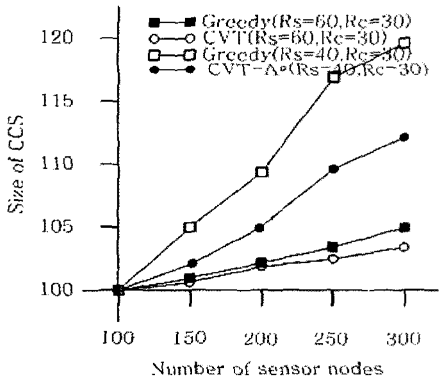

Fig 3. Performance comparison with Greedy

The size of the connected cover set constructed by greedy algorithm and CVT-A^* with different node number is showed in Figure 3. From Figure 3, we can see that our algorithm gets the smaller connected cover set compared with greedy algorithm whether R_c/R_s is lar-ger than 2 or not.

5.2 Experiment Results

Figure 4 shows how the size of CCS (i.e. the number of the working nodes) as well as the number of sensors that are turned off change with the initial sensor number, when $R_c/R_s=2$. We find that the size of the CCS is unchanged with different initial sensors randomly deployed when $R_c \geq 2R_s$. In reality, the size of CCS depends only on the sensing radius of sensor nodes when $R_c \geq 2R_s$ and is very similar to the smallest working node number (100) as expected. We must note that, here, the 100 nodes are not the initial fixing deployed 100 ones.

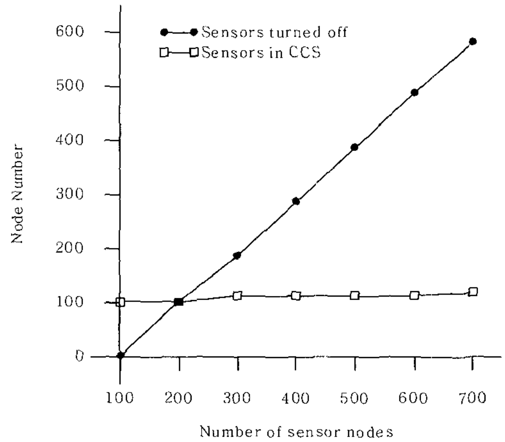

Fig 4. Results of CVT vs. node number ($R_c=60, R_s=30$)

Figure 5 shows how the size of the CCS and the sensors that are turned off change with the number of the initial sensors when $R_c=40$, $R_s=30$.

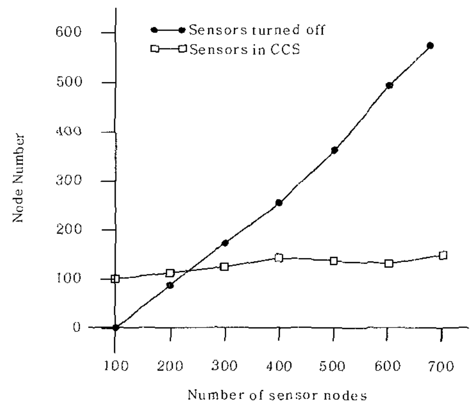

Fig 5. Results of CVT-A^* vs. node number ($R_c=40, R_s=30$)

VI. Conclusions & Future Works

This paper discusses the minimum connected cover set problem in wireless sensor networks. To settle this problem, we design an effective centralized algorithm. The basic idea is: construct the cover set first. The Voronoi Tessellation based CVT algorithm can get the near optimal cover set for the target area. When $R_c \geq 2R_s$, the cover set is connected at the same time; when $R_c < 2R_s$, we can not guarantee the connectivity of the cover set, so we design an A^* based connectivity scheme to calculate the assistant nodes needed to guar-antee the connectivity of the calculated cover set. Theoretical analysis and experimental results show that the algorithm we designed is superior to the greedy al-gorithm proposed in [1] in time complexity as well as the size of the finally calculated connected cover set. In the future, we will extend our solution to handle more sophisticated coverage models and connectivity config-uration and develop adaptive coverage reconfiguration for energy-efficient distributed detection and tracking techniques.

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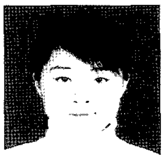
제 16 권 5 호(2006년 10월호) 참조



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