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Connected Target Coverage for Fully Data Gathering in Wireless Sensor Networks

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Abstract: Coverage problem is an important issue in wireless sensor networks, which has a great impact on the performance of wireless sensor networks. Many researches in this area only focus on how to cover all the targets in the network, which ignore considering the problem of how to transmit the sensing data to the sink. In this paper, we propose an energy-effective connected target coverage algorithm named ECTCG to guarantee the sensed data be effectively gathered in mobile wireless sensor networks. We theoretically analyze ECTCG algorithm and conduct extensive simulations to evaluate its performance. Simulation results show that ECTCG outperforms another existing algorithm CWGC by effectively prolonging the network lifetime.

Keywords: Wireless sensor networks, Target coverage, Data gathering.

1. Introduction

Wireless sensor networks (WSNs) [1-3] have many inexpensive wireless nodes, each capable of collecting, computing, storing, and processing environmental information, and communicating with neighboring nodes [4, 5]. Sensors usually adopt ad hoc networking technology to connect with each other, and transmit the gathered information to one or more than one sink [6, 7].

Target coverage problem is one of the measurements of WSNs QoS (Quality of Service). Given a sensor network, the coverage problem is to determine how well the sensing field is monitored or tracked by sensors, and how to maximize the network lifetime when all the targets are monitored is the most important problem in wireless sensor networks [8-10]. In many practical applications of WSNs, such as forest fires, nuclear leak, etc, we can convert these applications into target coverage problem, so the research of target coverage problem in WSNs has a very important significance.

Recently, the algorithms of target coverage issue in WSNs mainly concern about how to cover all the targets, without consider how to transmit the sensed data to the sink, therefore, in this paper, we will focus on how to effectively transmit the data to the sink based on the connected target coverage problem.

2. Related Work

The target coverage issue is a fundamental problem for wireless sensor networks. There are extensive numbers of studies about the target coverage problem. Reference [11] studied the connected target coverage problem in wireless sensor networks, and designed a distributed algorithm that did not need the global information of the whole network. Only needed the 3-hops information within neighbors, the algorithm could satisfy the requirement of coverage and connectivity, which was suitable for large-scale intensive sensor network.

Reference [12] proposed a connected target coverage algorithm with multiple sensing ranges of sensors in WSNs. The algorithm firstly constructed a virtual skeleton, and ensured that all nodes either existed in this virtual skeleton or could connect to a node in the virtual skeleton, and then the algorithm considered the goals of how to coverage all the targets in the network. But, it was unnecessary to build a global connected skeleton in many sensor network applications.

The node energy model in [13] took the data receiving energy and data sending energy into consideration, but the algorithm did not pay enough attention to consider the problem of how to transmit the data to the sink node, while only based on other routing mechanism to transmit the sensed data.

On the basis of reference [13], the algorithm in [14] modeled the connected target coverage (CTC) problem as a maximum cover tree (MCT) problem, and also proved that MCT is a NP-complete problem, and then gave an upper bound solution for MCT problem. Then, it developed an approximate algorithm named App_MCT and a greedy algorithm named CWGC. The basic idea of CWGC algorithm is to give each node and edge in the network a weight value, and then greedily choose proper nodes and edges to build a cover tree to execute the work task in each round. Finally, it used the extensive simulations to demonstrate the effectiveness of the App_MCT algorithm and CWGC algorithm.

3. Problem Statement

Before diving into solving the connected target coverage problem, firstly, we will give some fundamental definitions and notations in this section, which will be used throughout this paper, and then model this connected target coverage problem.

3.1. Network Model

Assume that s1, s2, … , sN are N sensors in a WSN and R is the sink. All sensors are randomly deployed to continuously cover M targets p1, p2, … , pM. S and P are two different sets of nodes, where S={ s1, s2,…, sN } (|S|=N) and P={ p1, p2,…, pM } (|P|=M). We use a directed graph G=(V, E) to represent the relationship among S(the set of sensor nodes), P (the set of target nodes) and R (the sink node), where V=S∪P∪R, E consists of transmission edges and coverage edges. If |si—sj|<rc , then (si, sj)∈E; else if |si—pj|<rs, then (si, pj)∈E.

Within the operation time, we use $S_s(\tau)$ to represent the set of nodes participating in the activity of monitoring objectives in the operation time τ , we use $S_r(\tau)$ to represent the set of nodes participating in the activity of transmission data in the operation time τ, and we use $S_a(\tau)$ to represent the set of active nodes in the operation time τ. Obviously, $S_a(\tau) = S_s(\tau) \cup S_r(\tau), S_a(\tau) \subseteq S$.

We have the following three assumptions: (1) each node will not change its Active/Sleep status within the operation time τ; (2) the sampling frequency for each node is the same; (3) the data cannot be aggregated in the network, when a node receives *N***B*(τ) data from all of its neighbors (*N* represents the number of neighbors), the data will be transmitted by the node directly.

3.2. Definitions

Definition 1: Connected Target Coverage (CTC) problem.

Given M targets with known location information and a WSN with N sensors randomly deployed in the area. Schedule the sensors' Active/Sleep activities so that all targets are continuously observed and the network can achieve a maximum network lifetime. The network must satisfy that: (1) each target must be continuously covered by at least one node; (2) the data of the targets can be transmitted to sink through active nodes' one-hop or multi-hops relay.

In order to solve the connected target coverage (CTC) problem, reference [14] modeled this problem as a maximum cover tree (MCT) problem.

Definition 2: Maximum Cover Tree (MCT) problem [14].

Given a directed graph *G*= (*V*, *E*), the initial energy of each node is E_0(s), where *V*=$S \cup T \cup R$. *E* consists of the communication edges and monitoring edges. There are a serial trees denoted by $T(\tau_1)$, $T(\tau_2)$,..., $T(\tau_d)$, and the operational time of these trees are denoted by τ_1, τ_2 …, τ_d, the network can achieve a maximum lifetime denoted as L. We can express this problem by the following mathematical representation:

Maximize L = $\sum_{i=1}^{d} \tau_i$

Subject to: $\sum_{i=1}^{d} E(s, T(\tau_i)) \leq E_0(s), \forall s \in S$,

where we use $T(\tau) = (S_s(\tau) \cup S_r(\tau), E(\tau))$ to represent the coverage trees constructed in operational time τ. The coverage tree has the following characteristics:

Sink is the root of the tree.

Each leave of the tree is a sampling node.

Each target can connect with at least one sampling node.

Each node in the coverage tree $T(\tau)$ uses the same energy consumption model which is used in [14].

$$E(s,T(\tau))=\begin{cases} e_s B(\tau)+e_{trans}P(\tau), s\in S_s(\tau)\ and\ s\notin S_r(\tau) \\ (e_{trans}+e_r)P(\tau)D(s,T(\tau)), s\notin S_s(\tau)\ and\ s\in S_r(\tau) \\ e_s Bit(\tau)+e_{trans}B(\tau)+ \\ (e_{trans}+e_r)P(\tau)D(s,T(\tau)),\ s\in S_s(\tau)\cap S_r(\tau) \\ 0,\ s\notin S_s(\tau)\ and\ s\notin S_r(\tau) \end{cases}$$

where $T(\tau)$ represents the trees constructed in operational time τ, $P(\tau)$ is the number of packets collected in operational time τ, e_s and e_r represent the energy dissipated by sensing and transmission of one bit data, respectively. e_{trans} represents the sending energy of a node, $e_{ij}^t = e_t + b\cdot d_{ij}^{\alpha}$ (where s_i is the sender, s_j is the receiver, d_{ij} is the distance between s_i and s_j, α is the attenuation factor of path, e_t and b are constant), so, $D(s,T(\tau))$ represents the number of offspring nodes of s in tree $T(\tau)$.

3.3. Upper Bound for MCT Problem

We will further model MCT problem into a LP problem in this section, and then prove that LP problem is exactly an upper bound for MCT problem. We will find the trees $T(\tau_1)$, $T(\tau_2)$,..., $T(\tau_d)$ in graph G. Then, we will model the MCT problem into a linear programming problem as follows:

L respects the network lifetime, s_i spends the duration time of t_{im} to monitor the target t_m, F_{ij} is the total number of data from s_i flow to s_i flow, F_{iR} is the total number of data flows from s_i to R.

Maximize L

$$\sum_{i=1}^{N} t_{im} - L = 0\ ;\ \forall p_m \in P \tag{1}$$

$$\sum_{j_i} F_{ij} + F_{iR} - \sum_{j} F_{ji} - f_s \sum_{p_m\in P} t_{im} = 0\ ;\ \forall s_i \in S \tag{2}$$

$$\sum_{j} F_{ij}\cdot e_{ij}^t + F_{iR}\cdot e_{iR}^t + \sum_{j} F_{ji}\cdot e_r + \sum_{p_m\in P} t_{im}\cdot f_s e_s \le E_0(s_i) \quad \forall s_i \in S \tag{3}$$

Theorem 1: The optimal solution of the above linear programming program is exactly the optimal solution's upper bound of MCT problem.

Proof: If we can prove that one optimal solution of MCT is also one feasible solution of the above LP problem, then, we can get the conclusion that the optimal solution of LP problem must be the optimal solution's upper bound of MCT problem.

Assuming that there are many solutions of MCT problem, such as

{$T(\tau_1)$, $T(\tau_2)$,..., $T(\tau_d)$}and{τ_1,…, τ_d}.

Each target can be covered at least once in the duration of the operating time τ_a, we can get that:

$$\sum_{i=1}^{N} t_{ima} = \tau_a\ ,\ \forall p_m \in P\ , \tag{4}$$

where t_{ima} represents the duration of s_i monitoring the target t_m within time τ_a. Equation (4) can also success in other operating time, where $a\in[1,d]$, so, we can get that:

$$\sum_{a=1}^{d}\sum_{i=1}^{N} t_{ima} = \sum_{a=1}^{d}\tau_a\ ,\ p_m \in P$$

That is to say, $\sum_{i=1}^{N} t_{im} - L = 0$, thus, Equation (1) is right, and Equation (2) and Equation (3) are also right, so, we can draw the conclusion that the optimal solution of the above linear programming program is exactly the optimal solution's upper bound of MCT problem, and we denote it as L_{LP}.

4. ECTCG Algorithm

Since MCT is a NP-complete problem [14], we present a fast heuristic algorithm named ECTCG (energy-efficient connected target coverage greedy algorithm) to solve the connected target coverage problem.

4.1. Design of ECTCG

The input of ECTGC are *S*, *T*, *R* and τ, the output of ECTGC are a series of cover trees ($T_1,\ldots,T_d$). For the sake of brevity in describing our algorithm in the following, we introduce some symbols that will be used in our algorithm here. Let s_i be the alive nodes set, $w(s_i)$ represents the path weight of s_i in ECTCG. B_i is the contribution of s_i. $R(s_i,T)$ represents the path of s_i to sink R in tree T, where $R(s_i,T)$=<s_i,s_j,…,R>. $\overline{R}(s,T)$ represents the set of node's paths in tree, except the source node s_i and the destination node R.

In a network with N sensors and M targets, the steps of constructing cover trees T_1 ,…, T_d are as follows:

1) At the beginning, the initial energy of each sensor is E_0, the number of the rounds is 1, denoted by d=1

2) Uncovered targets in the WSN, denoted by φ^d, sensors in d^{th} cover, denoted C_d, set φ^d= {all targets in the network}, C_d=Ø

Then, follow the below three steps:

Step 1: firstly, algorithm gives each directed edge a weight value, such as the weight value of directed edge <s_i,s_j> can be calculated by:

$$w_{ij} = \frac{e_{ij}^t \times E_0(s_i)}{E_r(s_i)}$$

For each node s_i in the network, find one path with the minimum weight value to the sink (such as using the Dijkstra algorithm)

Step 2: we use a greedy strategy to select nodes to cover all the targets.

(a) When all the targets cannot be completely covered, go to the step (b); otherwise, go to the step 3.

(b) Select a remote target x from all uncovered targets, α(x) is the number of sensors that can cover the target x, and the remote target x has a minimum α(x).

(c) Compute the weight value B_i of each node s_i as follows:

$$B_i = \frac{\theta_i}{w(s_i)},$$

where θ_i is the set of the uncovered targets within s_i' sensing range, and w(s_i) is the path weight value of s_i, which is exactly the sum of weight value of all edges in $R(s_i,T)$.

(d) Select a node s_i with the maximum contribution that can cover the remote target x, then add s_i into C_d.

(e) For node s_j, which satisfy $s_j \in \overline{R}(s_i, T_d)$, update:

$$w(s_j) = w(s_j) + (e_{trans} + e_r)P(\tau) \times w(s_j) / E_r(s_j)$$

and B_j, then go to step (a).

Step 3: Add the selected sampling node and $\overline{R}(s,T)$ into tree T, then update the residual energy of sensors according to their energy model.

In every round, the algorithm will be finished in the following time:

$$\tau_d = \min(\tau, \min_{s \in T_d}(\frac{E_r(s)}{E_s(\tau, T_d)}\tau))$$

Steps (2)-(3) are iteratively executed until all the targets can no longer be continuously covered. A specific description of ECTCG is shown in Fig. 1.

Algorithm ECTCG:
1. set sense range as r and energy of each sensor as e;
2. set the initial energy of each sensor s_i as E_0, $E_r(s_i)=E_0$
3. d = 1
4. while all the targets can be covered by active nodes, do
5. **step 1:** for each edge (s_i,s_j) in the network, compute $w_{ij} = e_{ij}^t \times E_0(s_i) / E_r(s_i)$
6． for each node s_i, find out one path with the smallest weight value to sink.
7. **step 2**：
8. $\varphi^d = \cup P_j$, （$j=1…M$） , $C_d=\varnothing$, $T_d=\varnothing$, $\tau_d = \tau$
9. for each node s_i, compute $B_i = \frac{\theta_i}{w(s_i)}$
10. while $\varphi^d \neq \varnothing$ do
11. select a remote target x from all the uncovered targets, which satisfy that:
α(x)< α(y), where $y \in \varphi^d$- ｛x｝ (if there exists more than one target x， select the nodes x that has the minimum ID number.)
12. construct a set S', any node s_i in set S' can cover target x, then select s_i from S' such that s_i can cover x and satisfy max B_i among all the sensors
13. $C_d = C_d \cup s_i$
14. $\varphi^d = \varphi^d - \rho_i$
15. for each node s_j that satisfy $s_j \in \overline{R}(s_i, T_x)$ do:
16. update $w(s_i) = w(s_i) + (e_{trans} + e_r)B(\tau) \times w(s_i) / E_r(s_i)$ and B_j
17. end while
18. **step 3:**
19. for each node s_i in C_d do: $T_d = T_d \cup R(s_i, T_d)$
20. for each node $s_i \in T_d$, $\tau_d = \min(\tau_d, \frac{E_r(s_i)}{E_s(\tau_d, T_d)}\tau_d)$
21. for each node $s_i \in T_d$, $E_r(s_i) = E_r(s_i) - E(s_i, T_d(\tau))$
22. $d = d + 1$
23. end while

Fig. 1. ECTCG algorithm.

4.2. Complexity of ECTCG

It is easy to know that the duration time for each round is τ or when a node is dead, so we can define the number of cover trees within the range of $N + L_{LP} / \tau$. The maximum complexity of each round is MN, therefore, the complexity of ECTCG is $O((N + L_{LP})MN / \tau)$， the same as that of CWGC.

5. Performance Evaluation

In this section, we will compare ECTCG with another typical algorithm CWGC, ECTCG and CWGC adopts the same methods to generate the skeleton of the tree to transmit the data, but they use different greedy strategies to select the source nodes. In the simulations, we will evaluate the metrics of network lifetime among above two algorithms.

We simulate a network with sensors and targets randomly deployed in a 100 m × 100 m area, the sink is located in the center of the area, and its coordinate is (50,50). We assume that each node has the same initial energy of 20 Joule (J), the other parameters are set as: $e_t = 50nJ/bit$, $b = 100pJ/m^4$, $\alpha = 4$, $e_r = 150nJ/bit$, $e_s = 150nJ/bit$, the data sampling frequency is 10 kbps, all the nodes have a same sensing radius of r_s and a some transmission radius of r_c, where r_s=20 m and r_c=40 m.

5.1. The Relationship between ECTCG and Parameter τ

At first, we study the performance of ECTCG by varying the value of parameter τ. There are 60 sensors and 20 targets that are randomly scattered in the area, we set τ as τ =0.1 % L_{LP}, 0.2 % L_{LP}, 0.4 % L_{LP}, 0.6 % L_{LP}, 0.8 % L_{LP}, 1 % L_{LP}, 2 % L_{LP}, 4 % L_{LP}, 6 % L_{LP}, 8 % L_{LP} and 10% L_{LP} respectively. The simulation results are shown in Table 1.

Table 1. The relationship between lifetime of ECTCG and τ.

τ/L_{LP}	ECTCG	τ/L_{LP}	ECTCG
0.1 %	2968.8	1 %	2892.4
0.2 %	2956.1	2 %	2501.1
0.4 %	2940.9	4 %	2404.4
0.6 %	2923.7	6 %	2304.7
0.8 %	2902.4	8 %	2301.5

From Table 1, we can see that the network lifetime becomes larger when the parameter τ becomes smaller. The smaller the τ, the more trees can be generated by ECTCG algorithm; the cost of the algorithm will become larger. So, we will set τ =1 % L_{LP} in the following simulations to balance the network lifetime and the cost of the algorithm.

5.2. The Performance Comparison between ECTCG and CWGC

We assume there are 20 targets in the area, and we vary the number of sensors from 50 to 130 with an increment of 10, respectively. The network lifetime of these two algorithms under different number of sensors are shown in Fig. 2.

From Fig. 2, we can see that, when compared with CWGC algorithm, ECTCG can enlarge the network lifetime to a certain extent as well as ensure all the targets be covered and the network be connected.

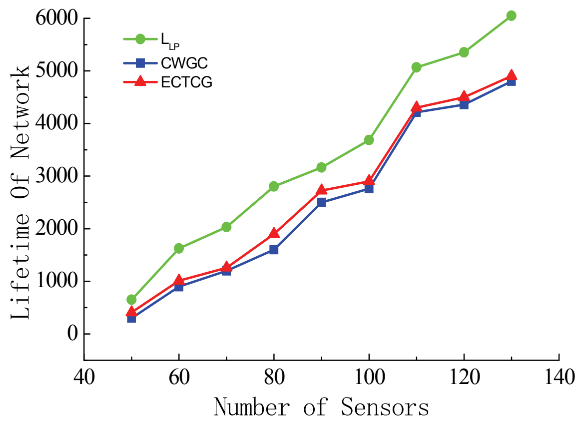

Fig. 2. The comparison of network lifetime between ECTCG and CWGC.

5.3. The Performance Comparison with Different Size of the Network

We compare the performance of ECTCG and CWGC under different size of network, and here we set two scenes, scene 1 (network of small size): there are 80 sensors and 10 targets in this scene; scene 2 (network of big size): there are 200 sensors and 25 targets in this scene. We set network delay as 20 and 10, respectively. The simulation results of network lifetime of different algorithms are shown in Table 2.

Table 2. The relationship between network lifetime and the size of the network.

	Lifetime (scene 1)	Lifetime (scene 2)
ECTCG	2460.3	6312.2
CWGC	2190.8	5324.5

In Table 2, ECTCG achieves a larger network lifetime than CWGC in the same complexity of algorithm, no mater how does the network size vary. Obviously, ECTCG gains a good performance than that of CWGC.

6. Conclusions

In this paper, we study the connected target coverage problem in wireless sensor network. We model the connected target coverage problem as a maximum cover tree (MCT) problem, and then we give an upper bound value for MCT problem. Since MCT is a NP-complete problem, we then develop a fast heuristic algorithm, named ECTCG to solve the MCT problem. Simulation results show that ECTCG can achieve a better performance than other existing algorithms.

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