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Energy conserving based k-coverage algorithm for dense wireless sensor networks

***Abstract**. As the energy supply of wireless sensor is limited, it is important to dynamically configure wireless sensor networks by correctly setting the on/off status of each sensor to let every target be k covered. In this paper, we propose an energy-efficient distributed target k-coverage algorithm for dense heterogeneous wireless sensor networks with multiple sensing units. To save the energy of sensors more efficiently, the sensing ability and the remaining energy of a given sensor is integrated to calculate sensor priority. The proposed approach is locally and simultaneously running at each sensor in a rounding mode. Each sensor should decide the on/off status of its sensing units at the beginning of each round, and then transmits this decision to its one-hop neighbours. The higher the priority of a sensor is, the shorter the decision time it needs. Experimental results show that compared with Energy First scheme and Integer Linear Programming solution, our approach has longer network lifetime than Energy First scheme, and the performance of our approach is second only to Integer Linear Programming solution.*

***Streszczenie.** W artykule zaproponowano energooszczędny algorytm dla gęstej, niejednorodnej sieci bezprzewodowej czujników. Każdy czujnik decyduje o stanie włączenia lub wyłączenia na początku każdej rundy testowania a następnie przeprowadzana jest transmisja danych do sąsiada. W zależności od priorytetu czujnika czas decyzji jest krótszy. (**Energooszczędny algorytm dla gęstej bezprzewodowej sieci czujników**)*

Keywords: Wireless Sensor Networks, Target Coverage, K-Coverage, Network Lifetime.
Słowa kluczowe: sieć bezprzewodowa czujników.

1. Introduction

Wireless Sensor Networks are made up of a large number of sensor nodes with radio communications, sensing, and low-power processing capabilities. One of the fundamental problems of WSN is to provide continuous coverage to ensure that each point is covered by at least one sensor. Particularly, for some specific applications, such as forest fire detecting and vehicle traffic monitoring, k-coverage (k>1) is required, which means that each point in the target area should be monitored independently by k sensors. Due to sensors' energy constraints, it is important to dynamically configure wireless sensor networks by using sleep/wakeup scheduling.

Mass production of sensor devices with low cost enables the deployment of large-scale sensor networks for real-life applications such as forest fire detection and vehicle traffic monitoring. A fundamental issue in such applications is the quality of monitoring provided by the network. This quality is usually measured by how well deployed sensors cover a target area. In its simplest form, coverage means that every point in the target area is monitored by, i.e., within the sensing range of, at least one sensor. This is called 1-coverage. In this paper, we consider the more general k-coverage (k⩾1) problem, where each point should be within the sensing range of k or more sensors.

Wireless sensor networks are often used for passive data obtaining or information monitoring in a given geographical region. Hence, an important problem is to how to maintain the fidelity of the sensed data while minimizing sensor's energy. There have been lots of efforts for target coverage problem for wireless sensor networks, but most of the previous studies concentrated on homogeneous wireless sensor networks with single sensing unit based on centralized policies. Wang et al. are the first to address the connected K-coverage problem. They propose a localized heuristic for the problem, but the proposed heuristic does not provide a guarantee of the solution size returned[1]. In [2], Poduri et al. used mobile sensor nodes to k-cover the target sensing field in short time under the constraint that for each sensor node, k other sensor nodes always exist in its proximity. Hefeeda and Bagheri [3] extended the well-known nets technique to solve the problem of k-covering the given sensor locations. The authors presented a novel approach to solve the k coverage problem in large-scale sensor networks. They modeled the k-coverage problem as a set system for which an optimal hitting set corresponds to an optimal solution for k-coverage. Furthermore, they proposed an approximation algorithm for computing near optimal hitting sets efficiently. The authors of paper [4] propose a distributed Coverage Configuration Protocol, which provides different degrees of coverage requested by applications. In [5], the authors formulate the k-coverage problem of a set of n grid points as an integer linear programming.

This paper addresses the energy-efficient target k coverage problem in dense heterogeneous wireless sensor networks. A distributed target k coverage algorithm for dense heterogeneous wireless sensor networks with multiple sensing units is presented to save the energy and prolong the network lifetime.

2. Explaination of K-coverage Problem

In order to simplify the target coverage problem, we make some restrictions and assumptions. Considering a number of targets with known locations that need to be continuously covered and a large number of sensors randomly deployed closed to the targets. We also assume the sensors have location determination capabilities, and all the sensors are built up randomly and can not be removed freely. Particularly, all the sensors have the same communication ability, computing ability and initial energy. Furthermore, supposing every sensor's communication distance is longer than twice of its sensing range so as to guarantee two sensors which can sense the same object can directly communicate to one-hop neighbours.

The wireless sensor networks discussed in this paper are heterogeneous and equipped with multiple sensing units, which means each sensor in the heterogeneous wireless sensor networks may be equipped with more than one sensing unit and the attribute each sensing unit can sense may be different as well. The number of sensors deployed in the sensing field is assumed to be bigger than the optimum needed to perform the target covering, so it is of great importance to decide correctly by which sensor the sensing attribute should be covered to make the power consumption minimized.

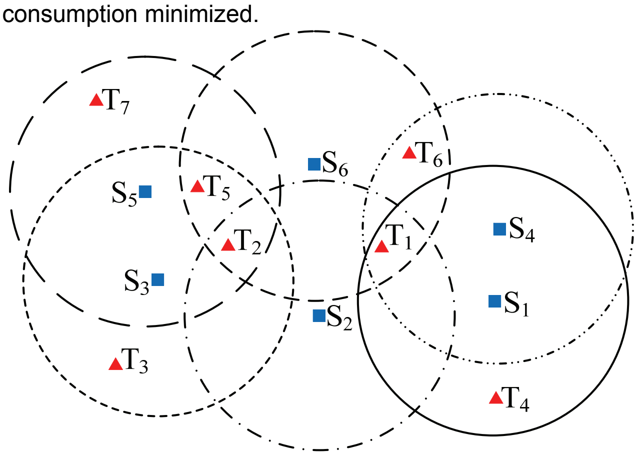

Fig.1. Example for K-Coverage problem with seven targets and six sensors

As is shown in Fig.1, target T1 together with T2 are 4-covered, and target T3,T4,T7 are 1-covered. Moreover, T5 and T6 are 3-covered and 2-covered respectively. The sensing area of a sensor is modeled as a circle centered at the sensor with radius as the sensing range.

Definition 1 A target in an area A is said to be covered only if it is within the sensor's sensing range.

Definition 2 Energy-efficient Target Coverage Problem for Heterogeneous Wireless Sensor Networks: Given a two-dimensional area A and a set of N heterogeneous wireless sensors $S=\{S_1,S_2,\ldots\ldots,\ S_N\}$, derive an schedule from every sensor to determine the on/off status of its sensing units such that: 1) the whole area A is covered. 2) The network lifetime is maximized.

Definition 3 Network lifetime is the duration during which the whole monitored targets are covered.

Target coverage in heterogeneous wireless sensor networks can be converted to Set Cover problem, then each set cover denotes the on/of status of sensing units in heterogeneous wireless sensor networks[6]. In [7], the coverage problem is formulated as integer linear programming(ILP) to obtain the optimal results. It is well known that solving ILP is an NP-complete problem. Due to limited energy and computing ability, it is impractical to use ILP to solve the heterogeneous wireless sensor networks target coverage problem on sensors. Therefore, we design a distributed heuristic algorithm for heterogeneous wireless sensor networks target coverage problem.

The K-Coverage problem is to select a minimal subset of nodes for activation to ensure all sensor locations are k-covered by the set of activated nodes. We follow the definition in [3] to formally explain k-Coverage Problem.

Problem 1 (k-Coverage Problem): Given *n* already deployed sensors in a target area, and a desired coverage degree $k\geq 1$, select a minimal subset of sensors to cover all sensor locations such that every location is within the sensing range of at least k different sensors. It is assumed that the sensing range of each sensor is a disk with radius r, and sensor deployment can follow any distribution.

The above k-coverage problem is proved to be NP-hard by reduction to the minimum dominating set problem. We propose an efficient approximation algorithm for solving the k-coverage problem.

3. Energy-efficient K-coverage Algorithm

3.1. Algorithm Overview

The network activity is organized in rounds, which means that each sensor runs this algorithm at the interval of a round time unit. Each round is made up of two phases(initial phase and the sensing phase). In the initial phase, all the sensors have to decide which sensing unit should be turned on in the sensing phase. To guarantee all the sensors' activities can be synchronized, we assume all the sensors have a clock with a uniform starting time.

3.2. Parameters Definition

To mathematically formulate this problem, the following notations need to be stated:

- *M*: The number of targets in sensing field.
- *N*: The number of sensors in sensing field.
- *P*: The number of sensing attributes.
- S_i:(i=1,2……N): The i^{th} senor.
- SA_i(i=1,2……N): The sensing ability of sensor *i*.
- α_k(k=1,2……P): The k^{th} sensing attribute.
- T_j(i=1,2…… M): The j^{th} target.
- A_{jk}: The sensing attribute α_k of target T_j
- $Num(A_{jk})$: The number of sensors which cover sensing attribute α_k of target T_j
- $ifkcov(A_{jk})$: When A_{jk} has been k-covered, the value of this parameter is true, otherwise false.
- θ_i: The sensing attribute set in which the attributes can only be covered by S_i.
- θ_i^l: The l^{th} sensing attribute in θ_i.
- $E\left(\theta_i^l\right)$: The energy consumption of θ_i^l in a round.
- E_i(i=1,2……N): The remaining energy of S_i.
- σ_i: The sensing attribute set in which the attributes can be covered by S_i excluding the ones in θ_i.
- σ_i^l: The l^{th} sensing attribute in σ_i.
- $E\left(\sigma_i^l\right)$: The energy consumption of σ_i^l in a round.
- β_i: The sensing attribute set in which the attributes will be covered by S_i in the sensing phase of the current round.
- *DT*: The duration of initial phase.
- *ST*: The duration of sensing phase.
- DT_i: The decision time of S_i.
- P_i: The priority of S_i. The higher priority of a sensor, the shorter time for it to determine the status of its sensing units.
- DM_i: The decision message of S_i.
- NB_i: The sensor set in which the sensors is the one-hop neighbors of S_i.

3.3. Computing Sensor's Priority

To prolong the network lifetime, the sensor's energy should be used efficiently. Two parameters should be considered carefully, which are the remaining energy and the sensing ability of the sensor. In the former researches, the two parameters have been put forward in some papers [6][8][9]. However, combining them to obtain a more reasonable policy has not been discussed.

To compute the sensor's priority, we should obtain its sensing ability at first. The value of SA_i can be computed as followings.

(1) $$SA_i=\sum_{m=1}^{|\sigma_i|}\frac{N}{\sigma_i^m}$$

As the attributes in θ_i can only be covered by S_i, the sensing units of S_i which can cover the attributes in θ_i must be turned on. Thus, there is no need to consider the attributes in θ_i.

In order to make the sensor priority decision more reasonable, we design a scheme to integrate SA_i and E_i together to compute the priority of S_i. There are two main principles in our scheme:

- The smaller the value of SA_i is, or the larger the value of E_i is, the higher the priority of S_i is.
- For any two sensors, if there is at least one parameter of the sensing ability and the remaining energy unequal, the priority of them is different as well.

Based on the two principles illustrated above, Eq.(2) and Eq.(3) are designed to compute P_i.

(2) $$\varepsilon_i = \left\lceil \frac{E_i - 2}{\delta} \right\rceil$$

(3) $$P_i = \frac{(SA_i + \varepsilon_i) \times \left[(SA_i - 1 - \varepsilon_i) \times \delta + 2E_i - 2 \right]}{2} + SA_i$$

We consider two characteristics of the sensing ability and the remaining energy in a priority table which is computed in advance and saved in the sensors localized. The ranges of these two parameters are divided into a number of different intervals, every which is represented by choosing a typical value. For any sensor with any sensing ability *SA* and remaining energy *E*, if *SA* and *E* is a typical relative sensing ability and a typical remaining energy respectively, the sensor's priority can be obtained by checking the priority table. If the priority is same, the sensor with a smaller ID wins. δ is a parameter which denotes the influence of sensing ability on sensor priority. The bigger the value of δ is, the much more influence exerted on sensor priority by sensing ability is. In section 4 and 5, we use δ =2 to compute sensors' priority. The value of δ can be adjusted when needed.

If one of *SA* and *E* is not among the typical values, the priority of the sensor can be calculated by interposing on the priority table. When the value of *SA* or *E* is arbitrary, we compute the sensor priority with the two-element three-point lagrange interpolation.

3.4. Algorithm Description

This algorithm runs on each sensor in the initial phase of each round distributively to decide the on/off status of each sensing unit in the sensing phase. For sensor S_i, the algorithm can be stated as follows.

Energy conserving based k-coverage algorithm

Input：**{** E_i, θ_i, σ_i, NB_i **}**
Output：Decide which sensing units should be turned on and broadcast the decision message to one-hop neighbors.
/*preparation phase*/
$SA_i = \sum_{m=1}^{|\sigma_i|} \frac{N}{\sigma_i^m}$;
/*For S_i, executing the following steps in the initial phase of each round*/
$E_i = E_i - \sum_{l=1}^{|\theta_i|} E(\theta_i^l)$;
computing P_i and exchanging it with one-hop neighbors;
$DT_i = \left(1 - \frac{P_i}{max\{\{P_w \mid \forall w, S_w \in NB_i\} \cup P_i\}}\right) DT$;
/*Listening to neighbors continuously for DT_i time to make its own decision*/
$\beta_i = \sigma_i$;
while DT_i is not expired **do**
  if receiving DM_y and $(\beta_y \cap \beta_i) \neq \emptyset$ **then**
    $\beta_i = \beta_i - (\beta_y \cap \beta_i)$;
  end if
end while
 if $E_i < \sum_{l=1}^{|\sigma_i|} E(\sigma_i^l)$ then /* The remaining energy is not sufficient*/
  return coverage can't continue;
else
  for each attribute α_x which is belonged to $\beta i \cup \theta_i$
   if $ifkcov(\alpha_x)$ =false then
    turn on the sensing units which can cover the attributes α_x ;
    $Num(\alpha_x)$ ++, $\alpha_x \in \beta i \cup \theta_i$;
    if $Num(\alpha_x)$ =*k* then
     $ifkcov(\alpha_x)$ =true;
    end if
    broadcast DM_i to one-hop neighbors;
   end if
  end for
end if

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4. Experimental results

We design a simulator with C++ to evaluate the efficiency of the proposed algorithm. Our simulations are based on a stationary network with sensor nodes and targets randomly located in a 400m$\times$400m area. We assume the sensing units are randomly assigned to sensors with the number not exceeding upper bound which is set in advance. Without loss of universality, the energy consumption of a sensing unit in a round is assumed equal to its ID. All the sensors are supposed to have the same initial energy(50 units). The sensing range of each sensing unit is set as 50m. The communication range of each sensor is twice of the sensing range. The initial phase lasts 8 seconds, and the duration of a round is 10 minutes. In the experiments, all the measurements are averaged over 15 runs to make the results more accurate. Energy consumption in communication and computation is omitted. In addition, a reliable communication channel is also assumed. The performance of the proposed is compared with ILP solution and energy first scheme(EF)[8] which is a greedy approach to make decisions for a sensor to enable its sensing units only considering its remaining energy. The ILP solution is implemented by the optimization toolbox in Matlab. We study on the performance of 2-coverage in this experiment.

In experiment 1, we measure the network lifetime when the number of sensors varies between 10 and 100, and the number of targets and attributes are respectively fixed to 25 and 4. The network lifetime increases with the number of sensors, as more sensors provide more opportunities to cover the targets(shown in Fig. 2).

Experiment 2 measures the impacts of the number of targets on the network lifetime, when the number of targets and attributes are respectively equal to 100 and 4. From the results we know the network lifetime decreases with the number of targets, because more targets consume more energy to cover them(shown in Fig. 3).

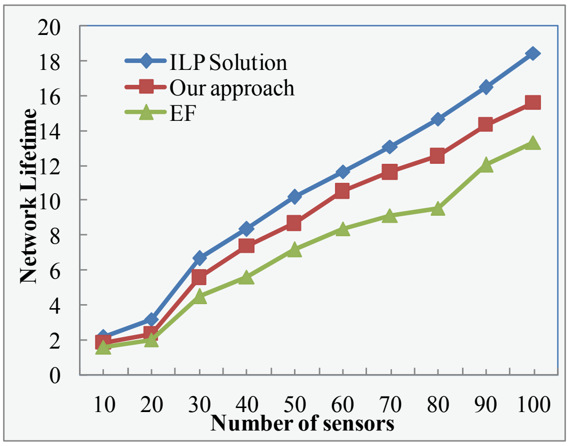

Fig.2. Network Lifetime with Number of Sensors

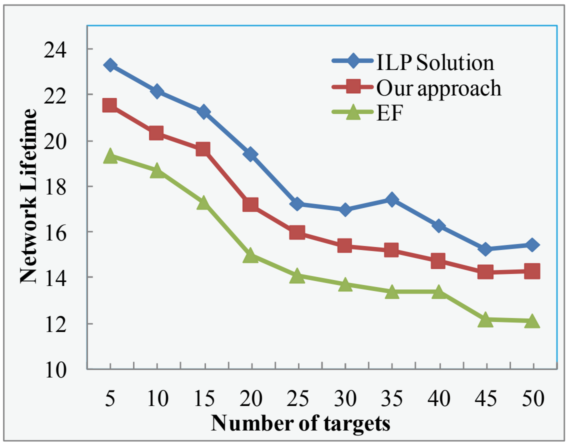

Fig.3. Network Lifetime with Number of Targets

Experiment 3 illustrates the relationship between network lifetime and the number of sensing attributes. We assume the number of sensors and targets are 200 and 25 respectively (shown in Fig. 4).

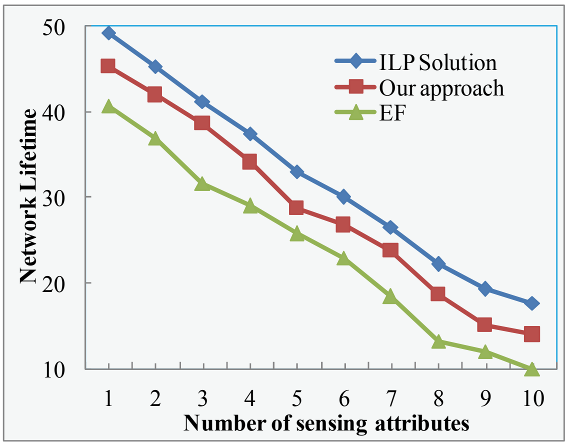

Fig.4. Network Lifetime with Number of Sensing Attributes

5. Conclusions

This paper investigates the energy-efficient target k coverage problem in heterogeneous wireless sensor networks with multiple sensing units. Different from the past work, this paper proposes a novel algorithm to solve the target k coverage problem. Experimental results are presented to show the advantages of our approach in the field of saving energy and prolonging network lifetime.

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