Energy Constrained Target K-coverage Algorithm in Heterogeneous Wireless Sensor Networks

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Abstract—**This paper presents a novel energy constrained target K-coverage algorithm, and the proposed algorithm is suitable to be exploited in heterogeneous wireless sensor networks. Particularly, the network activity in heterogeneous wireless sensor networks in this paper is organized in rounds, and each round is constructed by initial step and information sensing step. Furthermore, to prolong the network lifetime in target K-coverage process, the remaining energy and the sensing ability of each sensor are calculated in advance. Afterwards, the sensing unit set is defined to record sensing attributes that can be only covered by the target sensors. Furthermore, the attribute set contains several sensing attributes, and these attributes can cover the targets utilizing the specific sensing unit. In order to guarantee the K-coverage constraints, for each sensing attribute, we set a function to test whether the sensing attribute is covered. If the sensing attribute is covered by at least K sensors, the function return true, and then the decisions which represent if a sensor should be turned on or not are broadcast to each sensor's one-hop neighbors. Finally, a series of experiments are conducted to make performance evaluation. In these experiments, all targets and wireless sensors are randomly allocated in the sensing field, and six types of experimental settings with different number wireless sensor are utilized. Experimental results show that, our proposed algorithm performs better than EF method and KTC_MNL method, and the performance of our algorithm is close to the optimal method.**

Index Terms—**Heterogeneous wireless sensor networks, Target K-coverage, sensing unit, sensing attribute, Integer linear programming**

I. INTRODUCTION

Wireless sensor network is made up of a large number of resource-limited tiny devices, named sensors. A typical wireless sensor includes CPU, storage, battery power, and communication bandwidth. These sensors can sense task-specific environmental phenomenon, perform in-network processing on the sensed, and communicate wirelessly to other sensors or to a data gathering node, usually through multi-hop communications. Wireless sensor network can be utilized for a variety of applications dealing with monitoring, control, and surveillance[1]. Particularly, Wireless sensor networks have attracted a lot of attention recently due to the plenty of the applications and their connections with the physical world[2].

WSNs can be classified into two types, "homogeneous" and "heterogeneous", in terms of the capacities of sensor resources such as energy supply, memory space, processing power and communication bandwidth. A homogeneous WSN is composed of the sensors with similar or identical resource capacities. A heterogeneous WSN (HWSN) is made up of sensors with different levels of resource capacities. To balance sensor resource capacities in a HWSN, its sensor are often organized into a number of clusters. A sensor with a high level of resource capacity normally acts as a cluster head to provide a data aggregation point for its cluster members served by sensors with lower resource capacities [3].

In the research field of wireless sensor networks, coverage problems are fairly fundamental and crucial. The target coverage problem is finding an optimal scheduling for sensors such that the lifetime to detect every target can be as long as possible. However, the target coverage problem has been proved to be NP-complete[4]. Most of previous research work only considers one or two factors exclusively and thus fails to prolong the lifetime to near the optimum.

Furthermore, a high level of redundancy in wireless sensor networks can benefit for enlarging the network lifetime, as well as for improving the resilience of coverage and network connectivity. The target coverage problem can be classified into two kinds: 1) field coverage, where the overall field is covered by sensors and no coverage hole can be tolerated at any time, and 2) target coverage, where each target is monitored continuously by at least one sensor[5]. In this paper, we concentrate on the target coverage problem of wireless sensor networks.

On the other hand, energy efficiency is an important issue in wireless sensor networks since sensors are battery powered. Therefore, reducing power consumption and prolonging network lifetime are the primary challenges in the design of wireless sensor networks. In this paper, we focus on the target coverage problem with the objective of maximizing network lifetime and reduce energy constrained[6].

To enhance the system performance, the K-coverage problem is presented. K-coverage means that every target should be covered by at least k sensors, and a property

doi:10.4304/jsw.9.12.3048-3056

known as k-coverage, where the maximum value of k is called the coverage degree. The limited battery power of sensors and the difficulty of replacing and recharging batteries in hostile environments require that the sensors be deployed with high density in order to extend the network lifetime. Moreover, to cope with the problem of faulty sensors due to low battery power and achieve high data accuracy, redundant K-coverage of the same region is necessary[1].

Based on the above analysis, in this paper, we study on how to design an efficient target K-coverage algorithm in heterogeneous wireless sensor networks with the energy conserving policy. The main innovations of this paper lie in that we organize the network activity in heterogeneous wireless sensor networks in round mode, and we propose a function to test if a specific sensing attribute is covered.

II. Related Works

The target coverage problem of wireless sensor networks is often studied together with the network lifetime in existing research works.

In the field coverage category, Pazand presented an algorithm named MDS based on minimum dominating set without using GPS/location information. It finds many subsets of sensors, each of which guarantees a high level of field coverage, with the aim to extend the overall network lifetime[7].

Similarly, shen et al. present a novel density control algorithm called ESSC(Enhanced Sponsored Sector Coverage). ESSC can make full use of the Sponsored Sector Coverage concept. This method can prolong the network lifetime and provide a high degree of field coverage. Particularly, in this work, the authors presented ESSC algorithm takes note of the deficiency of the SSC algorithm and modifies the model of SSC to minimize the active node number based on the Sponsored Sector Coverage[8].

Gu et al. studied on the partial target coverage problem in wireless sensor networks under a novel coverage model. The authors showed that the partial target coverage problem can be optimally solved in polynomial time. First, they built a linear programming formulation considering the total time that a sensor spends on covering targets[9].

To prolong the network lifetime of wireless sensor network with multiple type sensors, the sensor need to monitor deployed targets. Hence, in paper [10], Mostafaei proposed an efficient scheduling method based on learning automata. In the proposed method, each node is equipped with a learning automaton to help the node selecting its proper state (active or sleep), at any given time.

Mini S. et al. aimed to examine phase-transition behavior of maximum lifetime target coverage problem in wireless sensor networks domain. This paper showed that as they vary the uniform sensing range of sensors, the number of hard instances of the problem sharply rises around a critical value independent of other parameters. To facilitate the hardness analysis, they devised a new and efficient algorithm to solve target coverage problem; this algorithm has the distinct ability of distinguishing hard problem instances[11].

Zorbas et al. described the problem of the minimum sampling quality, where an event must be sufficiently detected by the maximum possible amount of time. Since the probability of detecting a single target using randomly deployed static nodes is quite low, we present a localized algorithm based on mobile nodes. The proposed algorithm sacrifices a part of the energy of the sensors by moving them to a new location in order to satisfy the desired detection accuracy. It divides the monitoring process in rounds to extend the network lifetime, while it ensures connectivity with the base station. Furthermore, this paper propose two redeployment schemes that enhance the performance of the proposed approach by balancing the number of sensors between densely covered areas and areas that are poorly covered[12].

Montoya et al. proposes a MWSN architecture with an initial random distribution in a specific work area, and a centralized management to perform autonomous decision making about the movement and connectivity of the sensors. The work area presents mobile targets with interesting events. Particularly, these events must be covered by the mobile sensors, and thus, send the collected information through the network to any base station available[13].

Medagliani et al. addresses the problem of engineering energy-efficient target detection applications, using unattended Wireless Sensor Networks (WSNs) with random node deployment and partial coverage, for long-lasting surveillance of areas of interest. As battery energy depletion is a crucial issue, an effective approach consists in switching on and off, according to proper duty cycles, sensing and communication modules of wireless sensors [14].

Deng et al. discuss the energy-efficient area coverage problem considering boundary effects in a new perspective, that is, transforming the area coverage problem to the target coverage problem and then achieving full area coverage by covering all the targets in the converted target coverage problem[15].

However, in many cases, wireless sensors can be easily damaged or the sensed data is noised. Therefore, it should be ensured that each target in the sensing field must be covered by at least k sensors, such that even if some sensor fails or has no energy, the region covered by it still can be covered by other wireless sensors. It can be seen that target K-coverage algorithm can enhance the security and accuracy of the wireless sensor networks.

Zhao et al. concentrate on the problem of scheduling sensor activities to maximize network lifetime while maintaining both discrete K-target coverage and network connectivity. In K-target coverage, it is required that each target should be simultaneously observed by at least K sensors. The data generated by the sensors will be transmitted to the sink node via single or multiple hop communications.[16].

Yun et al. study on the deployment patterns to achieve full coverage and k-connectivity ($k <= 6$) under different ratios of the sensor communication range (denoted by

R(c)) to the sensing range (denoted by R(s)) for homogeneous wireless sensor networks (WSNs). They propose new patterns for 3- and 5-connectivity[17].

Ammari et al. propose the Reuleaux tetrahedron model to characterize k-coverage of a 3D field and investigate the corresponding minimum sensor spatial density. They prove that a 3D field is guaranteed to be k-covered if any Reuleaux tetrahedron region of the field contains at least k sensors. Furthermore, they compute the connectivity of 3D k-covered WSNs as well. [18].

Li et al. investigate the Sensor Scheduling for k-Coverage problem and find that solving this problem requires to efficiently schedule the sensors, such that the monitored area can be k-covered throughout the whole network lifetime with the purpose of maximizing network lifetime. The proposed problem is NP-hard and the authors propose two heuristic algorithms under different scenarios[19].

Yang et al. analyze the critical conditions for connected-k-coverage using the percolation theorem and demonstrate their effectiveness using simulation results. Connected-k-coverage has been recognized as an effective notion for prolonging the sensor network lifetime. [20].

Different from the above methods, the novelty of the proposed method lie in that 1) Each round of the wireless sensor network is made up of initial step and information sensing step, and 2) To guarantee the K-coverage constraints, a decision function is presented for each sensing attribute to test if the sensing attribute is covered.

III. The Proposed Scheme

Fig.1 shows an example of target K-coverage problem in wireless sensor networks is illustrated. In order to ensure the system security, each target is covered by K sensors, that is, each target is located in the sensing range of at least K wireless sensors.

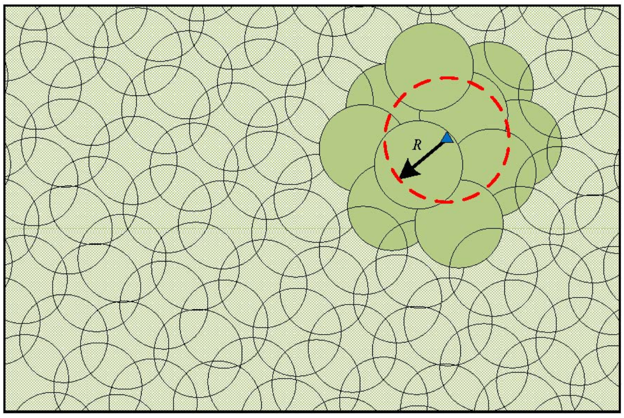


Fig.1 An example of target K-coverage problem in wireless sensor networks

In this paper, the network activity in heterogeneous wireless sensor networks is organized in rounds. This design means that each sensor runs this algorithm at the interval of a round time unit. Each round consists of two steps: 1)initial step and 2)information sensing step. In the first phase, all the wireless sensors should decide which sensing unit should be turned on in the second step. To make all the sensors' activities can be synchronized, all the sensors are assumed to have a clock with a uniform starting point.

Firstly, the formal description of the energy constrained target K-coverage problem[21,22] in heterogeneous wireless sensor networks is given through the parameters definition.

Definition 1 (Energy constrained target K-coverage problem in heterogeneous wireless sensor networks): Given an integer K, and the condition $K>0$ is satisfied. The proposed problem aims to find a subset of sensors $C \subseteq V$, and then the following conditions are satisfied:

i) Each sensor node in the set V could be covered by at least K different wireless sensors in set C.

ii) The number of wireless sensors in set C is minimized.

iii) The wireless sensors in set C are connected with each other.

Furthermore, the proposed target K-coverage problem can be converted to an integer programming as follows. Supposing there are n wireless sensors($N_1, N_2, \cdots, N_n$), and α_{ij} denotes the coefficients which represent the coverage relationship between different wireless sensors. Particularly, α_{ij} can be computed as follows.

$$\alpha_{ij} = \begin{cases} 1, \textit{if the node } N_i \textit{ can be sensed by } N_j \\ 0, \qquad \textit{otherwise} \end{cases} \quad (1)$$

Next, the variables $x_j (j \in \{1, 2, \cdots, n\})$ represent boolean values.

$$x_j = \begin{cases} 1, \textit{if the node } N_j \textit{ can be selected in set } C_j \\ 0, \qquad \textit{otherwise} \end{cases} \quad (2)$$

Based on the above analysis, the energy constrained target K-coverage problem can be represented as follows.

$$\text{Minimize } \sum_{i=1}^{n} x_i$$

$$\text{S.T. } \sum_{j=1}^{n} \alpha_{ij}, x_j \geq k, i \in \{1, 2, \cdots, n\}$$

$$x_j \in \{0, 1\}, i \in \{1, 2, \cdots, n\} \quad (3)$$

We can see that the condition $\sum_{j=1}^{n} \alpha_{ij}, x_j \geq k$ can ensure that each wireless sensor in the set V can be covered by at least K sensors in the set C.

Assuming that there is a wireless sensor work with N sensors having the ability to provide sensing coverage to a set of m target in the given region. Particularly, the sensors in the sensing range are randomly located. Supposing that N denotes the set of all the wireless sensors and T represents the set of all the targets. Before we provide the target K-coverage algorithm, some important definitions should be given in advance.

Definition 2 (**Sensor utility**): Sensor utility of sensor $N_i (U(N_i))$ means the total number of the target points $t \in T$, and the points are located in the range of the sensor N_i.

Definition 3 (**Coverage**): Target coverage of a given target $t\,(C_S(t))$ refers to the total number of sensors covering the target t.

Definition 4 (**Cover utility**): Cover utility of the cover $C_S(t)$ is defined as follows.

$$U(C) = \sum_{N_i \in C} U(N_i) \tag{4}$$

Definition 5 (Set Coverage): Coverage of a set T for the target points which are related to the wireless sensors set is defined as follows.

$$C_S(T) = \sum_{t \in T} C_S(T) \tag{5}$$

To enhance the network lifetime in target K-coverage process, the sensor's energy should be utilized with high efficiency. Therefore, the remaining energy and the sensing ability of a given sensor should be calculated accurately. To calculate sensor priority, we should obtain its sensing ability in advance. The value of sensing ability for the sensor N_i is obtained by the following equation can be computed as followings.

$$A_i = \sum_{m=1}^{|\tau_i|} \frac{N}{\tau_i^m} \tag{6}$$

In the next section, the sensing attribute set that can only be covered by N_i is represented as d_i. Hence, the sensor priority of sensor N_i can be calculated as follows.

$$P_i = \frac{1}{2} \cdot (A_i + \gamma_i) \times \left[(A_i - 1 - \gamma_i) \times \tau + 2E_i - 2 \right] + A_i \tag{7}$$

where the parameter γ_i is used to modify the influence of sensing ability on sensor priority, and γ_i is computed through Eq.8.

$$\gamma_i = \left\lceil \frac{E_i - 2}{\tau} \right\rceil \tag{8}$$

Based on the above analysis and related definitions, the target K-coverage algorithm is illustrated as follows.

Algorithm1: Energy conserving based k-coverage algorithm for wireless sensor networks

Input:Number of sensors, the sensing range, number of targets, number of sensing attribute, K

Output:Determining that which sensor should be turned on to assure that all the targets could be covered by at least K sensors.

1) Computing the sensing ability(K) of all sensors;

2) Computing the energy of all sensors:

$$E_i = E_i - \sum_{l=1}^{|d_i|} E\left(d_i^l\right);$$

3) Integrating E_i and A_i to obtain the sensing priority P_i by Eq.7

4) Setting the decision time in which the neighbor sensors are listened continuously.

5) Define μ_p as the sensing unit set, that can be enabled by the sensor N_p to cover the sensing attributes, and the sensing attributes can only be covered by N_p.

6) Define ν_p as the attribute set containing the element β_{jk}, and β_{jk} represents the sensing attribute covering the target t_j with the sensing unit σ_k

7) Swapping the information of μ_p and ν_p with neighbors of each sensor.

8) **For** all sensing attribute β_{jk} belonged to ν_p

9) **For** the sensors belonged to one of the neighbors of N_p and they can cover target t_j utilizing σ_k.

10) **If** $\beta_{jk} \in \mu_p$ and the remaining energy of sensor N_v is larger than N_u

11) $\nu_p = \nu_p - \{\beta_{jk}\}$

12) **End if**

13) **End for**

14) **End for**

15) **For** each sensing attribute β_{jk} belonged to ν_p

16) Defined the function $is\_cover(\beta_{jk})$ to show whether the sensing attribute β_{jk} is covered.

17) **If** $is\_cover(\beta_{jk})$=false then

18) Turn on the sensing units which can cover the attributes β_{jk};

19) $N(\beta_{jk}) = N(\beta_{jk}) + 1$

20) **If** $N(\beta_{jk}) = K$ then

21) $is\_cover(\beta_{jk})$=true;

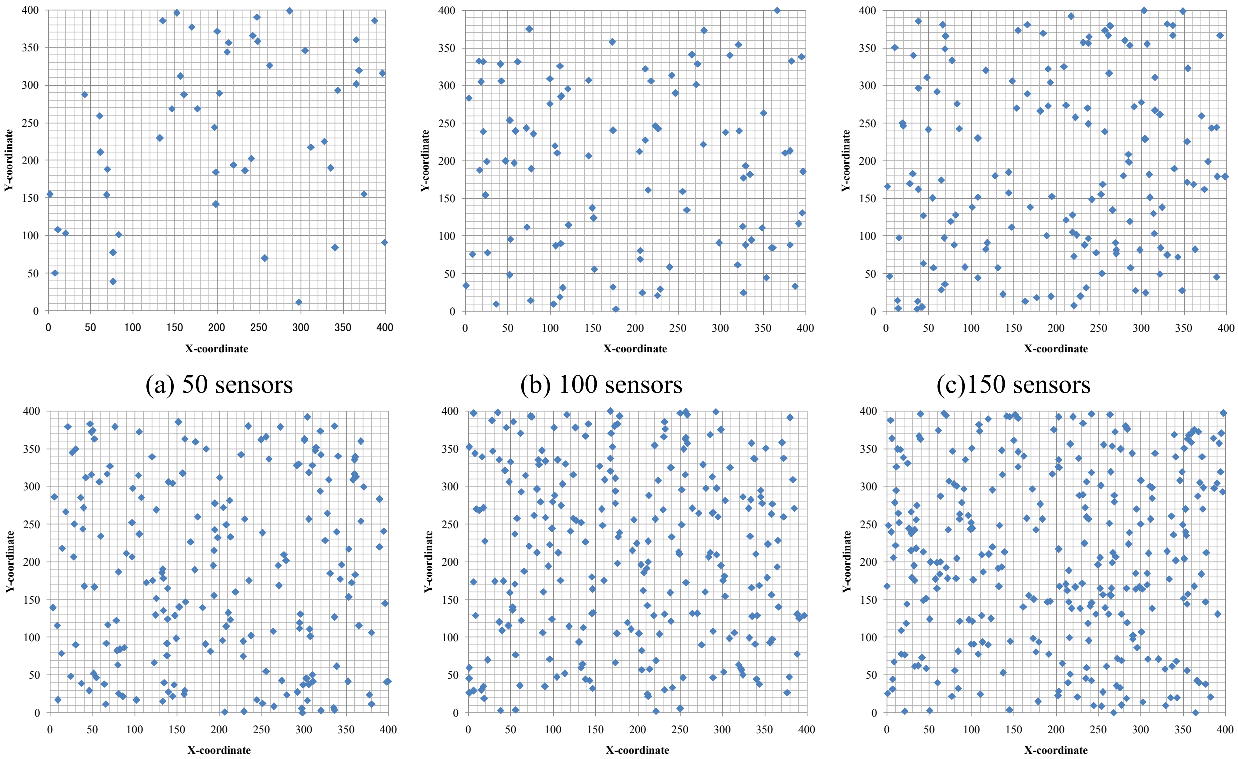
22) **End if**

23) broadcast all the above decisions to each sensor's one-hop neighbors

24) **End if**

25) **End for**

26) **End if**



(a) 50 sensors (b) 100 sensors (c)150 sensors

(d) 200 sensors (e) 250 sensors (f) 300 sensors

Fig. 2 Illustration of six types of sensors in the sensing field

IV. Experiments

A. Experimental Settings

Before analyzing the experimental results, the experimental settings should be illustrated in detail. We select OMNET++[25] as the simulation tool in this expriment. OMNET++ refers to the Modular discrete event simulator implemented in C++. Furthermore, OMNET++ provides a powerful GUI library for animation and tracing and debugging support. Particularly, the topologies of the wireless sensor network used in this experiment are shown in Fig.2, and routing algorithm used in this paper is presented in paper [26].

Parameters of experimental settings are explained in advance (shown in Table.1). In the proposed experimental settings, the numbers of wireless sensors and targets are limited for each simulation setting. Furthermore, the number and types of sensing units on sensors are constrained for each simulation as well, and the number and types of sensing units on each wireless sensor are randomly chosen. Meanwhile, the number and types of sensing attributes which are needed to be sensed at each target are chosen in a random mode. Particularly, all targets and wireless sensors are randomly allocated in the sensing field, and six types of experimental settings with different number wireless sensors are utilized. As is shown in Fig.2 (a)-(f), six types of sensors installation mode in the sensing field is described. To be short, the allocation of sensors and sensing targets are not allowed to be changed in the simulation process. The sensing range of each sensing unit is fixed to be 60 meters.

Moreover, the communication range of each sensor is equal to two times of the sensing range distance. To make the experimental results more objective, all experiments are executed 15 times, and the final results are obtained by averaging all the 15 experiments.

TABLE.I
PARAMETERS OF EXPERIMENTAL SETTINGS

Description	Value
Sensing range	$60m$
Area of sensing field	$400m \times 400m$
Communication range	$120m$
Number of wireless sensors	$\{50, 100, 150, 200, 250, 300, 350\}$
Number of sensing attributes	$\{2,3,4,5,6,7,8,9\}$

In table.2, the value of energy conserving for each working state of wireless sensors is given, and three sensor working states are considered: 1) active state, 2) transmitting state and 3) receiving state.

TABLE.II
THE VALUE OF ENERGY CONSERVING FOR EACH WORKING STATE OF WIRELESS SENSORS

Description of sensor working state	Energy consumption(mA)
Active state	11.25
Transmitting state	12.07
Receiving state	7.18

Afterwards, relationship between the sensing unit and its energy consumption should be explained (shown in Table.3). In this table, each sensing unit in our experimental settings and its energy consumption is presented.

TABLE.III
RELATIONSHIP BETWEEN THE SENSING UNIT AND ITS ENERGY CONSUMPTION.

The sensing unit id	Energy consumption(J / min)
u_1	1
u_2	2
u_3	3
……	……
u_l	l

B. Experimental results and related analysis

To make the experimental analysis more objective, three methods are compared with the proposed algorithm. In paper [23], the wireless sensor networks' target 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 the limited energy and computing ability, it is not possible to utilize ILP solution to solve the target K-coverage problem in heterogeneous wireless sensor networks. Further, the ILP solution is implemented by the optimization toolbox in Matlab.

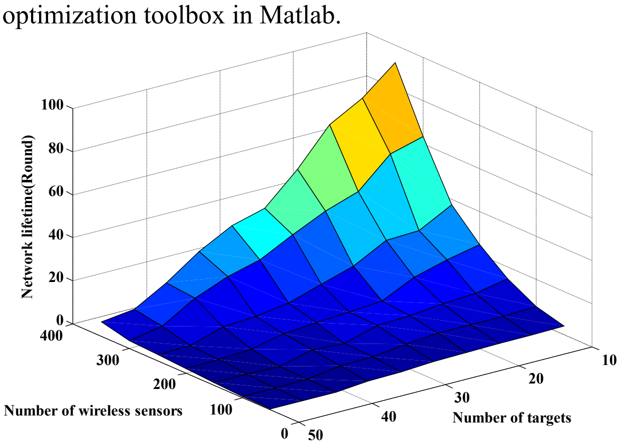


Fig.3 Network lifetime for our proposed algorithm under scheme 1

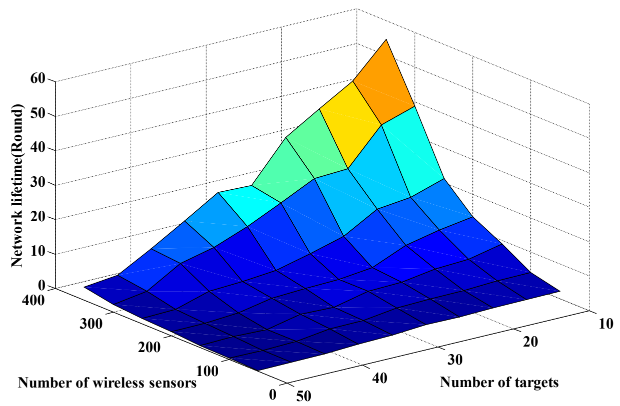


Fig.4 Network lifetime for EF under scheme 1

Another method we chose to compare with our methods is proposed in paper [24](denoted as "Energy first scheme(EF)"). EF is a greedy approach to make decisions for a sensor to enable its sensing units only considering its remaining energy. The algorithm in Paper [16](denoted as "K-target coverage with maximize network lifetime"(KTC_MNL)) is compared with ours as well. In paper [16], the authors aims to solve the problem of scheduling sensor activities to maximize network lifetime while maintaining both discrete K-target coverage and network connectivity.

Firstly, we test the energy efficiency for each method by the standard metric "Network lifetime" with the number of targets and number of wireless sensors changing. Considering the ILP solution is the optimal approach for energy constrained wireless sensors target K-coverage, and there are no control and computation overheads in ILP solution. We design two experimental schemes to make performance evaluation, that is, 1) scheme 1: all the methods are compared with the ILP solution to show the efficiency without the control and computation overheads, where the ILP solution is implemented by matlab tool box optimization library, and 2) Scheme 2: the above methods are evaluated considering the control and computation overheads.

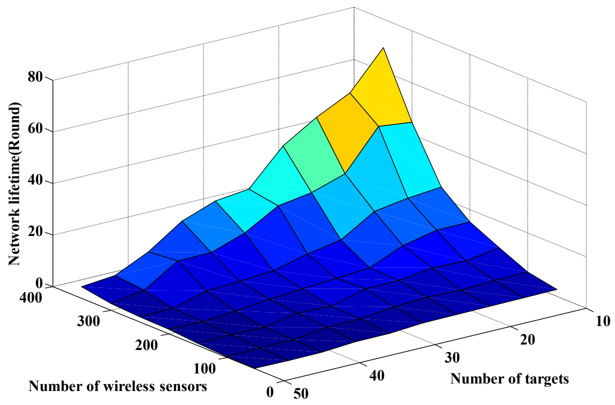


Fig.5 Network lifetime for KTC_MNL under scheme 1

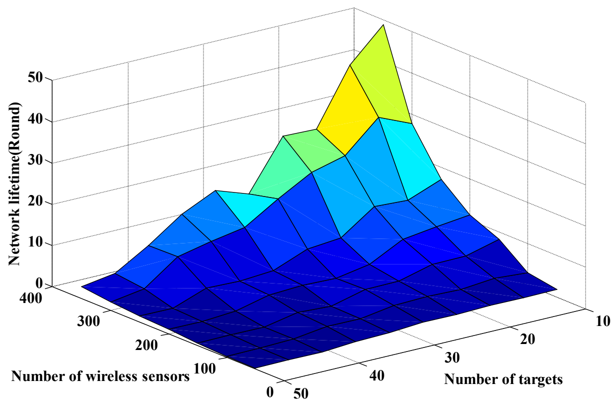


Fig.6 Network lifetime for our proposed algorithm under scheme 2

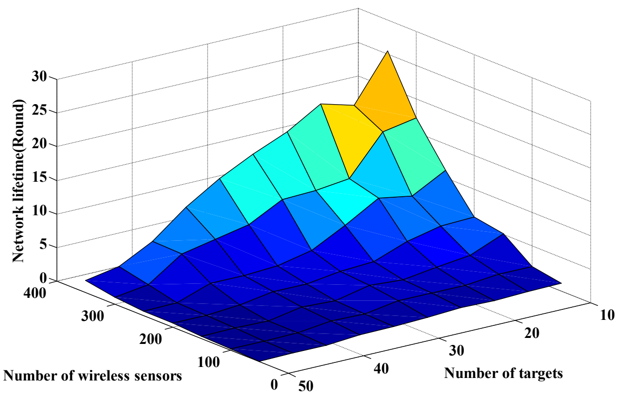


Fig.7 Network lifetime for EF under scheme 2

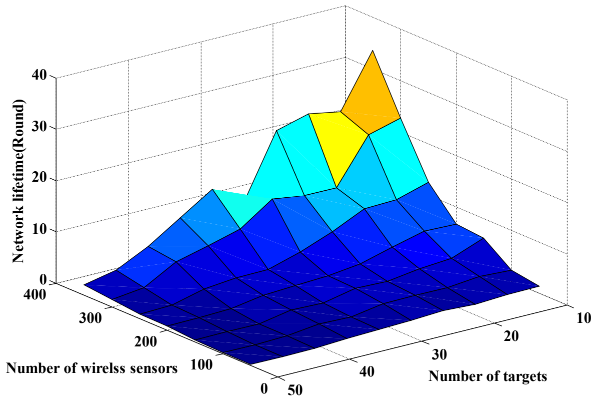


Fig.8 Network lifetime for KTC_MNL under scheme 2

Fig.3-Fig.8 shows the performance of our proposed algorithm, EF method and KTC_MNL method in a comprehensive mode which integrates the numbers of wireless sensors and targets to test their influence on the network lifetime. Particularly, the unit of the network lifetime we used is “Round”. In this experiment, the number of wireless sensors is set from 50 to 350 with a step of 50, the number of targets is varied from 10 to 50 with a step of 10, and the number of attributes is fixed at 4. It can be seen from Fig.3-Fig.8 that all the methods under scheme 1 performs better than scheme 2. The reasons lie in that all in scheme 1 we do not consider the control and computation overheads in target converge process. However, in scheme 2, these factors are all considered in target coverage to enhance energy consumption.

On the other hand, we find that our proposed algorithm performs better than EF and KTC_MNL.

From Fig.9, we can see that the network lifetime can be prolonged with the number of sensors increasing for all the methods. Because the targets covered by more sensors can enhance the network lifetime and reduce the energy consumption as well. As the ILP is an optimal solution, it can be regarded as the performance evaluation metric. Comparing with the ILP solution, the performance of network lifetime of EF method, KTC_MNL and our proposed algorithm decreasing 36.85%, 17.25% and 12.78% respectively.

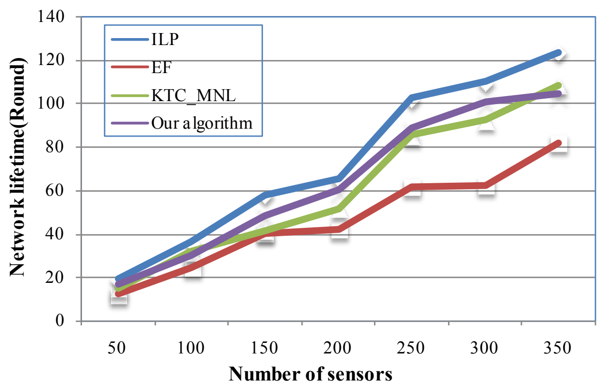


Fig.9 Network lifetime evaluating with number of sensors changing

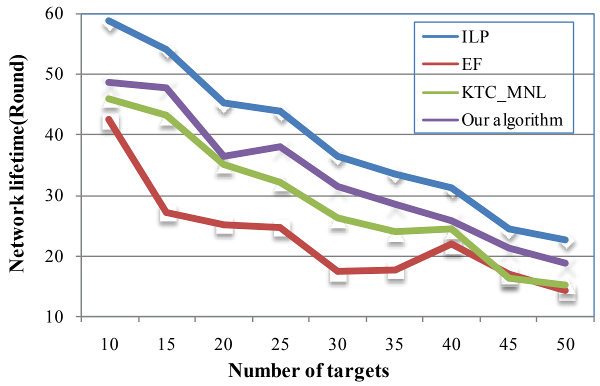


Fig.10 Network lifetime evaluating with number of targets changing

Fig. 10 gives the experimental results of network lifetime with number of targets increasing. The conclusions can be drawn from the data in Fig.10 that for all the methods, network lifetime reducing with the number of targets increasing. The reasons lie in that if the number of targets increases, additional energy consumption of sensors are increasing as well. Regarding the ILP solution as baseline, the performance of network lifetime of EF method, KTC_MNL and our proposed algorithm decreasing 40.45%, 24.88% and 15.25% respectively.

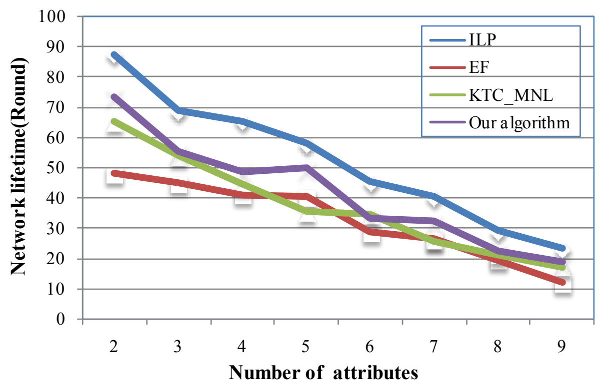


Fig.11 Network lifetime evaluating with number of attributes changing

As this paper aims at the heterogeneous wireless sensor networks, energy consumption should be tested with different number of sensing attributes. In Fig.11, network lifetime evaluating with number of attributes enhancing is demonstrated. When the number sensing attributes increasing, network lifetime decreases obviously for all methods, because more sensing attributes would increase the computation of wireless sensor networks. Based on the ILP performance, the performance EF method, KTC_MNL and our proposed algorithm decreasing 37.47%, 28.62% and 19.93% respectively.

V. Conclusions

In this paper, we propose energy constrained target K-coverage algorithm for heterogeneous wireless sensor networks. Firstly, the remaining energy and the sensing ability of each sensor are computed. Secondly, the sensing unit set and the attribute set are defined. Thirdly, a function is designed to test if the sensing attribute is covered. Fourthly, if the sensing attribute is covered by at least K sensors, the function return true, and then the finally decisions are transmitted to each sensor's one-hop neighbors. Finally, experimental results show the effectiveness of our proposed algorithm.

Although this paper proposed an effective constrained target K-coverage algorithm, there are some aspects to be improved and deeply studied. In the future, the sensor with more than one sensing unit should be considered, and the sensors with different sensing ranges should also be taken into account. Particularly, other simulation platform and routing algorithm will be exploited in the experiment.

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