On Target Coverage in Wireless Heterogeneous Sensor Networks with Multiple Sensing Units*

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Abstract

The paper considers the target coverage problem in wireless heterogeneous sensor networks (WHSNs) with multiple sensing units. The paper reduces the problem to a set cover problem and further formulates it as integer programming (IP) constraints. Moreover, two heuristic but distributed schemes, Remaining Energy First Scheme (REFS) and Energy Efficient First Scheme (EEFS), are proposed to solve the target coverage problem. Simulation results show that REFS and EEFS effectively prolong the network lifetime. In addition, EEFS outperforms REFS in network lifetime.

1 Introduction

A wireless heterogeneous sensor network (WHSN) is a kind of wireless sensor networks (WSNs) but each sensor may have different capability, such as various transmission capability, different number of sensing units, and so on [4, 5]. In the paper, the WHSN with multiple sensing units means that each sensor in the WHSN may equip with more than one sensing unit and the *attribute* that each sensing unit can sense may be different as well. To construct such a WHSN is cost-effective and power-efficient if multiple attributes are required to be sensed in the sensing field. The reasons are as follows. On one hand, in addition to the sensing unit, a sensor, in general, consists of a control unit, a power unit, a radio unit, and so on. If each sensor equips with only one sensing unit, it will raise the cost substantially to deploy all kinds of sensors to sense all attributes required. On the other hand, if all sensing units are equipped in a sensor, the sensor will run out of energy soon. Therefore, a WHSN with multiple sensing units is a promising way to be deployed if multiple attributes are required to be sensed in the sensing field.

In a WSN, coverage is one important issue and also a key factor to measure the success of the WSN. The target coverage problem can be regarded as one of coverage problems. However, slightly different from the above problems, the target coverage problem is, given a set of targets (or points) of interest, to schedule sensors to cover the set of targets as long as possible [2, 3, 6]. The definition of the target coverage problem in WHSNs with multiple sensing units, named MUT problem (**M**ultiple Sensing **U**nit for **T**arget Coverage problem) in the paper, is given as follows.

Definition 1 (MUT Problem) *Given some targets and a number of sensors with multiple sensing units randomly deployed in the vicinity of the targets, the MUT problem is to schedule the on/off mode of sensors' sensing units such that all the attributes at each target are continuously sensed and the network lifetime is maximized.* □

The MUT problem can be represented by a bipartite graph and be reduced to a set cover problem, named MUST problem (**M**ultiple Sensing **U**nits **S**et Cover for **T**arget Coverage problem) in the paper. Furthermore, the MUST problem can be formulated as an integer programming (IP) problem and be solved by an IP solver. In practical viewpoint, two distributed schemes, named REFS and EEFS, are proposed to deal with the target coverage problem. In REFS (Remaining Energy First Scheme), a sensor enables its sensing units depending on its remaining energy and neighbors' decisions. The advantages of REFS are its simplicity and less communication overhead incurred. However, the sensing redundancy is the most significant weakness of REFS. As a result, in order to use the sensor's energy efficiently, another scheme, called Energy Efficient First Scheme (EEFS), is proposed as well. In EEFS, except the

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remaining energy, a sensor enabling its sensing units still considers its sensing capabilities and the efficiency of each sensing unit. The distributed schemes aim at prolonging the network lifetime and monitoring all targets with all sensing attributes. From simulation results, both REFS and EEFS can prolong the network lifetime efficiently. It is worth mentioning that, to our best knowledge, this paper is the first one to discuss the target coverage problem in WHSNs with multiple sensing units.

The rest of the paper is organized as follows. Section 2 describes the related work regarding to the target coverage problem. Section 3 explains the target coverage problem and formulates the problem to IP constraints. In Section 4, the schemes, REFS and EEFS, are proposed to deal with the target coverage problem. Simulation results are presented in Section 5. Section 6 concludes the paper.

2 Related Work

Recently, the target coverage problem attracts a lot of attention [2, 3, 6]. In [2], the authors transformed the target coverage problem into a *maximal set cover problem*. The goal of the problem is to schedule the activity of sensors to cover the given targets completely and maximize the network lifetime. The authors proposed a linear programming based heuristic algorithm and a centralized greedy algorithm. However, these algorithms are not distributed.

The target coverage problem considering adjustable sensing range was discussed in [3]. Prolonging the network lifetime was also the goal of the problem. The authors used a bipartite graph to represent the coverage relation between sensors and targets. Moreover, the target coverage problem was transformed to an *adjustable range set cover problem* and was formulated as IP constraints. An LP-based heuristic, a centralized greedy, and a distributed greedy algorithms were proposed as well. On the other hand, the target coverage problem emphasizing on k-coverage and network connectivity was discussed in [6]. Given k, it requires each target being covered by at least k sensors and those active sensors being connected. In the paper, an LP-based centralized algorithm and two distributed algorithms are proposed. Although considering target coverage problem, the above papers only considered that each sensor equips with only one sensing unit. Therefore, the paper investigates the target coverage problem with multiple sensing units.

In [2], the maximal set cover problem considering the sensor with single sensing unit has been revealed to be an NP-complete problem. The target coverage problem of heterogeneous sensors with multiple sensing units is a superset of that of homogeneous sensors with only one sensing unit. Thus, the target coverage problem of heterogeneous sensors with multiple sensing units is also an NP-complete problem.

3 Problem Statements and IP Constraints

The paper assumes that sensors are randomly and stationarily deployed around targets. Each sensor is equipped with different numbers and types of sensing units, each of which corresponds to one sensing attribute. The sensing range of each sensing unit is assumed the same and is unadjustable. The communication range of each sensor is also assumed the same. Let R_s and R_c denote the sensing range of a sensing unit and the communication range of a sensor, respectively. For simplicity, the paper also makes the assumption that $R_c \geq 2R_s$.

On the other hand, the energy consumed by different types of sensing units in a time unit is different. However, the initial energy of each sensor is assumed the same. Besides, each sensor can be aware of its location and obtain one-hop neighbor information via communication. Moreover, the locations of the targets to be sensed are known by sensors in advance and will not change during the whole sensing period. An attribute on a target is said to be covered if the target is located within the sensing range of the sensing unit corresponding to the indicated attribute.

3.1 Problem Statements

Suppose there are M targets, denoted $t_m, m = 1, 2, \ldots, M$, to be monitored. There are N sensors, denoted $s_n, n = 1, 2, \ldots, N$, randomly deployed in the vicinity of the M targets. There are L attributes, denoted $a^l, l = 1, 2, \ldots, L$, to be sensed for each target. Attribute a^l can be sensed by the sensing unit u^l, for $l = 1, 2, \ldots, L$. The energy consumption of the sensing unit u^l in a time unit is e^l, for $l = 1, 2, \ldots, L$. The initial energy of each sensor is E. Without loss of generality, the index variables listed below are used for corresponding purposes.

- m: m^{th} target, where $1 \leq m \leq M$,
- n: n^{th} sensor, where $1 \leq n \leq N$, and
- l: l^{th} attributes, sensing unit, or energy consumption of the l^{th} sensing unit, where $1 \leq l \leq L$.

Take Fig. 1 as an example. There are two targets, t_1 and t_2, as well as three attributes, a^1, a^2, and a^3, to be sensed by five sensors, $s_1, s_2, \ldots, s_5$, as shown in Fig. 1 (a). In the figure, different circles mean the differences of sensing capabilities of sensors. Fig. 1 (b) illustrates the corresponding coverage relationship in terms of sensing units on sensors and attributes at targets by means of a bipartite graph, where u^l_n and t^l_m stand for the sensing unit u^l on sensor s_n and the attribute a^l at target t_m, respectively. If the sensing unit u^l on sensor s_n can sense the attribute a^l at target t_m, there exists a ray from u^l_n to t^l_m. In the figure, the different types of rays mean the different types of sensing units.

From the bipartite graph, the MUT problem can be regarded as a set cover problem. Sensors as well as their

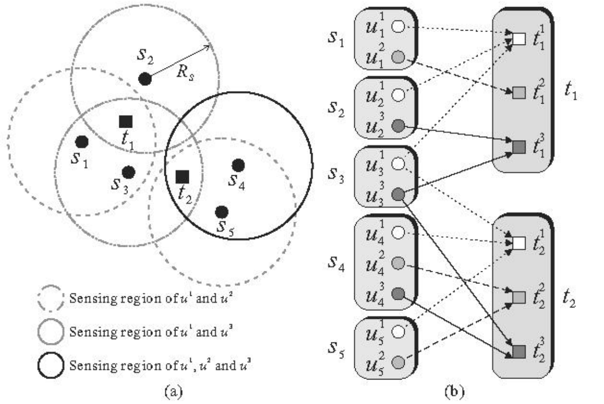

Figure 1. An illustrated example: (a) the topology, (b) the coverage relationship.

sensing units are organized as set covers. In each set cover, sensors and sensing units required to be turned on should cover all attributes at all targets. Take Fig. 1 as an example. The set $\{u_1^2, u_3^1, u_3^3, u_4^2\}$ can cover attributes a^1, a^2, and a^3 for all targets t_1 and t_2. Therefore, $\{u_1^2, u_3^1, u_3^3, u_4^2\}$ is a set cover. Formally, the MUST problem is defined as follows.

Definition 2 (MUST Problem) *Given M targets and N sensors with multiple sensing units randomly deployed in the vicinity of the targets, the MUST problem is to find a family of set covers c_1, c_2, ..., c_K, such that (1) K is maximized, (2) all attributes at each target can be covered by each set cover, and (3) the energy consumption of each sensor in all set covers is at most E.* □

Notice that, each set cover corresponds to a working period, say a *round*, for sensors and selected sensing units on these sensors. Thus, in the definition of the MUST problem, maximizing K is equal to maximize the network lifetime.

3.2 IP Constraints for MUST Problem

By Definition 2, the MUST problem can be formulated as integer programming (IP) constraints as follows.

IP Constraints for the MUST Problem

Given:

- M targets: $t_m, m = 1, 2, \ldots, M$,
- N sensors: $s_n, n = 1, 2, \ldots, N$,
- Initial energy of each sensor: E,
- L sensing attributes: $a^l, l = 1, 2, \ldots, L$,
- L sensing units: $u^l, l = 1, 2, \ldots, L$, which respectively senses the attribute $a^l, l = 1, 2, \ldots, L$, and energy consumed is: $e^l, l = 1, 2, \ldots, L$,
- $u_{n,m}^l$: the coefficients indicates whether target t_m can be sensed by sensor s_n with the sensing unit u^l; $u_{n,m}^l = 1$ if sensor s_n can use sensing unit u^l to sense target t_m; otherwise, $u_{n,m}^l = 0$, $\forall\, m = 1, 2, \ldots, M$, $\forall\, n = 1, 2, \ldots, N$, and $\forall\, l = 1, 2, \ldots, L$.

Variables:

- c_k: boolean variable; $c_k = 1$ if c_k is a set cover; otherwise, $c_k = 0$, $\forall\, k = 1, 2, \ldots, K$, where K is an upper bound of the number of set covers,
- $\hat{u}_{n,k}^l$: boolean variable; $\hat{u}_{n,k}^l = 1$ if sensor s_n enables the sensing unit u^l in set c_k; otherwise, $\hat{u}_{n,k}^l = 0$, $\forall\, n, l, k$.

Objective: Maximize $c_1 + c_2 + \cdots + c_K$.
Subject to:

(C1) $\sum_{n=1}^{N}(u_{n,m}^l * \hat{u}_{n,k}^l) \geq c_k, \forall\, m, l, k,$
(C2) $\sum_{k=1}^{K}\sum_{l=1}^{L}(\hat{u}_{n,k}^l * e^l) \leq E, \forall\, n,$
(C3) $\hat{u}_{n,k}^l \in \{0, 1\}, \forall\, n, l, k,$
(C4) $c_k \in \{0, 1\}, \forall\, k.$

Constraints (C1) and (C2) correspond to the second and the third requirements in Definition 2. Note that, it is well-known that solving IP is an NP-complete problem. Therefore, two distributed schemes to solve the target coverage problem in WHSNs are proposed as follows.

4 Distributed Schemes for the MUT Problem

Two distributed schemes, named REFS (Remaining Energy First Scheme) and EEFS (Energy Efficient First Scheme), are proposed to solve the MUT problem, where time is divided into rounds of equal period. Each round is further divided into an *initial phase* and a *working phase.* The proposed distributed schemes are run in every initial phase for each sensor to determine which sensing units on the sensor should be turned on in the following working phase. In addition to its current status, each sensor makes the decision only by one-hop neighbor information.

4.1 Remaining Energy First Scheme (REFS)

REFS is a greedy approach, which takes the sensor's remaining energy and neighbors' decisions into consideration to make decisions for a sensor to enable its sensing units.

Let δ_n^l be the sensing capability of the sensing unit u^l on sensor s_n, if sensor s_n is equipped with u^l, where the sensing capability of a sensing unit means the attribute and the targets (in terms of t_m^l) that the sensing unit can sense. Consequently, $\delta_n^l = \{t_m^l | d(t_m, s_n) \leq R_s, \forall\, m\}$, where $d(x, y)$ is the Euclidean distance between x and y. Furthermore, let Δ_n be the *sensing capability* of sensor s_n, which is the set of sensing capabilities of all sensing units equipped on s_n. That is, $\Delta_n = \{\delta_n^l | \forall\, u_n^l\}$. For the example shown in Fig. 1,

$\delta_1^2 = \{t_1^2\}$ and $\delta_3^1 = \{t_1^1, t_2^1\}$. In addition, $\Delta_1 = \{\delta_1^1, \delta_1^2\} = \{\{t_1^1\}, \{t_1^2\}\}$ and $\Delta_3 = \{\delta_3^1, \delta_3^3\} = \{\{t_1^1, t_2^1\}, \{t_1^3, t_2^3\}\}$.

REFS is a self-pruning approach. Initially, a sensor, say s_n, will take all t_m^l that it can sense as its sensing responsibility. Let Γ_n denote the *sensing responsibility* of s_n. At the beginning of an initial phase of each round, Γ_n is initialized to $\bigcup_{\forall u_n^l} \delta_n^l$. For the example shown in Fig. 1, $\Gamma_1 = \delta_1^1 \cup \delta_1^2 = \{t_1^1, t_1^2\}$ and $\Gamma_3 = \delta_3^1 \cup \delta_3^3 = \{t_1^1, t_2^1, t_1^3, t_2^3\}$. After that, each sensor waits for a period of time to listen to neighbors' decisions and then makes a decision to turn on the sensing units indicated in Γ_n for the the following working phase. The waiting time of each sensor solely depends on the remaining energy of the sensor. The more the energy remains, the shorter the waiting time is. Let W denote the duration of an initial phase and W_n denote the waiting time of sensor s_n. Note that W is much less than the duration of a round. Let E_n^r stand for the remaining energy of sensor s_n, for $n = 1, 2, \ldots, N$. Thus, W_n can be set as $(1 - \frac{E_n^r}{E}) * W,\ n = 1, 2, \ldots, N$.

During W_n, s_n prunes out those t_m^l revealed in the decision packet from its sensing responsibility, once receiving neighbor's decision packet. Upon W_n expired, the remaining Γ_n is the sensing responsibility of s_n at this round. However, it is possible that even exhausting all remaining energy of s_n still can not support all sensing units indicated in Γ_n to operate during the whole working phase. As a result, s_n orderly removes the sensing unit whose sensing capability is the weakest, that is, the number of targets that the sensing unit can sense is the smallest. Finally, s_n will enable the corresponding sensing units indicated in the remaining Γ_n. Similarly, s_n will also announce its decision by sending out a **DecAnn** packet. Note that, s_n stops executing REFS and turns off all the sensing units, if having no enough energy to enable any sensing unit. The remaining energy of s_n will leave for communication, not for sensing.

Overall, REFS is a simple and easy to be implemented scheme. Moreover, REFS incurs less communication overhead. However, the efficiency of a sensing unit does not take into account in REFS. Therefore, REFS has a high possibility to enable more redundant sensing units.

4.2 Energy Efficient First Scheme (EEFS)

Like REFS, EEFS is also a self-pruning approach and is operated at the initial phase by each sensor to distributively decide the on/off mode of each sensing unit for the following working phase. The behavior of EEFS is very similar to that of REFS, but adds more heuristics to prune the redundant or inefficient sensing responsibilities. The details of EEFS are shown in Algorithm 1.

Before executing EEFS, each sensor has to collect its and neighbors' sensing capabilities and critical sensing responsibilities in advance to efficiently make use of the sensing

Algorithm 1: Energy Efficient First Scheme (EEFS)

Input:
- $\Delta_n = \{\delta_n^l | \forall\, u_n^l\}$, $\Theta_n = \{t_m^l | t_m^l$ is only covered by $u_n^l.\}$.
- $\Delta_{n'}$, $\Theta_{n'}, \forall\, n' \in \aleph(n)$.

Result: Decide Γ_n and broadcast a **DecAnn** packet.

begin
  Exchange E_n^r with neighbors ;
  $\Gamma_n = \bigcup_{\forall u_n^l} \delta_n^l$;
  foreach u_n^l **do**
    $\mathcal{L} =$ Sort $\delta_{n'}^l, \forall u_{n'}^l |_{n' \in \{n\} \cup \aleph(n)}$ into a list, according to the priorities (1) $|\delta_{n'}^l|$ (2) E_n^r, or (3) ID in an increasing order ;
    $r_n^l =$ the order of δ_n^l in the list $\mathcal{L}$;
    $r_{max}^l = |\mathcal{L}|$;
  $\rho_n = \sum_{\forall u_n^l} \frac{r_n^l}{r_{max}^l}$;
  $W_n = (1 - \frac{E_n^r}{E} * \frac{\rho_n}{|\{u_n^l\}|}) * W$;
  while W_n *is not expired* **do**
    if **DecAnn** *packet is received, say from* $s_{n'}$ **then**
      $\Gamma_n = \Gamma_n - \Gamma_{n'}$;
  foreach u_n^l **do**
    foreach $n' \in \aleph(n)$ **do**
      if $\delta_{n'}^l \cap \Theta_{n'} \neq \emptyset$ **then**
        $\Gamma_n = \Gamma_n - \delta_{n'}^l$;
  foreach $t_m^l \in \Gamma_n$ **do**
    foreach $n' \in \aleph(n)$ **do**
      if $s_{n'}$*'s* **DecAnn** *packet is not received* **and** $Eff(s_{n'}, u^l) > Eff(s_n, u^l)$ **then**
        $\Gamma_n = \Gamma_n - \{t_m^l\}$;
        break ;
  if $\Gamma_n \neq \emptyset$ **then**
    while $\sum_{l|_{t_m^l \in \Gamma_n}} e^l \geq E_n^r$ **do**
      $\Gamma_n = \Gamma_n - \{t_m^{l'} \in (\Gamma_n - \Theta_n), \forall\, m \mid l' = l|_{\min_l |\{t_m^l, \forall\, m | t_m^l \in \Gamma_n\}|}\}$;
    Enable all sensing units u^l, if $t_m^l \in \Gamma_n$;
    Pack **DecAnn** packet to include Γ_n ;
    Broadcast **DecAnn** packet ;
end

units of its own. The critical sensing responsibility of a sensor is the attributes and the targets (in terms of t_m^l) which can be sensed only by the sensor. Let Θ_n be the critical sensing responsibility of sensor s_n. $\Theta_n = \{t_m^l | t_m^l$ is only covered by $u_n^l.\}$. For the example shown in Fig. 1, $\Theta_1 = \{t_1^2\}$. In other words, each sensor, e.g. s_n, has to compute Δ_n and Θ_n as well as to collect $\Delta_{n'}$ and $\Theta_{n'}, \forall\, n' \in \aleph(n)$, in advance, where $\aleph(n)$ denotes the neighbors of s_n. Formally, $\aleph(n) = \{n' | d(s_{n'}, s_n) \leq R_c\}$.

At the beginning of EEFS, each sensor has to exchange its remaining energy information (E_n^r) with its neighbors. In addition, s_n has to rank its sensing priority among its neighbors to decide the waiting time, W_n, in order to let a sensor with higher priority and more remaining energy make the decision earlier. The ranking is processed as follows. If s_n equips with the sensing unit u^l, s_n will sort $\delta^l_{n'}$ to a list L according to $|\delta^l_{n'}|, \forall\ n' \in \{n\} \cup \aleph(n)$ in an increasing order. If the sensing capability is the same, the larger the remaining energy is, the higher the priority is. Otherwise, the sensor with a larger ID wins. Notice that only the sensor equipped with u^l is included in the ranking process. Let r^l_n be the order in the sorted list, which means the priority of u^l_n among its neighbors. The larger the r^l_n is, the higher the priority of u^l_n is. Moreover, let r^l_{max} be the number of sensors included in the ranking process of u^l. It is worth mentioning that the reason to take a rank among the neighbors is to avoid from information hiding due to the different scale of numbers.

Take s_1 in Fig. 1 as an example. Since $\aleph(1) = \{2, 3\}$, only s_1, s_2, and s_3 are taken into account. Suppose $E = 8$, $E^r_1 = 6$, $E^r_2 = 8$, and $E^r_3 = 4$. Since s_1 equips with u^1 and u^2, r^1_1 and r^2_1 as well as r^1_{max} and r^2_{max} are to be calculated. Firstly, u^1 is considered. Obviously, $|\delta^1_1| = 1$, $|\delta^1_2| = 1$, and $|\delta^1_3| = 2$. Since $|\delta^1_1| = |\delta^1_2| = 1$, the remaining energy is taken into account. Therefore, the priority of δ^1_1 among s_1 and its neighbors is: $\delta^1_1 < \delta^1_2 < \delta^1_3$. Consequently, $r^1_1 = 1$ and $r^1_{max} = 3$. With regard to u^2, since s_2 and s_3 do not equip with u^2, therefore, $r^2_1 = 1$ and $r^2_{max} = 1$.

Let ρ_n be the priority of s_n, which takes the priorities of all sensing units equipped on s_n into consideration. ρ_n can be obtained by the summation, $\sum_{\forall u^l_n} r^l_n / r^l_{max}$. For the above example, $\rho_1 = \frac{1}{3} + \frac{1}{1} = \frac{4}{3}$. In order to not only take the remaining energy into account, but also consider the sensing efficiency of a sensor, W_n can be set as $(1 - \frac{E^r_n}{E} * \frac{\rho_n}{|\{u^l_n\}|}) * W$, where $\frac{\rho_n}{|\{u^l_n\}|}$ is an average priority of sensing units equipped on s_n. Notice that $0 < \frac{\rho_n}{|\{u^l_n\}|} \leq 1$. With regard to the above example, the value is equal to $\frac{4}{3}/2 = \frac{2}{3}$. Thus, the sensor with both more remaining energy and higher priority can make the decision earlier.

Then, the following statements from line 10 to line 12 Algorithm 1 are to prune the redundant t^l_m which has been decided to be covered by the neighbors indicated from their **DecAnn** packets. The pruning procedure of EEFS is similar to that of REFS. Upon the expiration of W_n, the remaining Γ_n is the sensing responsibility of s_n at this round. However, it is still possible for s_n to alleviate its burden via pruning out more sensing responsibilities which either shall be covered by neighbors or shall be left for the neighbors with higher sensing efficiency. The goal of the statements shown from lines 13 to 16 in Algorithm 1 is to prune the sensing responsibilities of s_n which can be covered by its neighbors. It is because, for some neighbor, say $s_{n'}$, if $\Theta_{n'} \neq \emptyset$, $s_{n'}$ has the responsibility to cover the sensing responsibilities indicated in $\Theta_{n'}$. If $s_{n'}$ turns on u^l, for some l, to cover t^l_m ($\in \Theta_{n'}$), for some m, turning on the sensing unit is also possible to cover the other targets, say $t^l_{m'}$, for some m'. That is, $t^l_{m'} \in \delta^l_{n'}$. Therefore, if $t^l_{m'} \in \Gamma_n$, $t^l_{m'}$ can be pruned from Γ_n since $t^l_{m'}$ must be covered by $s_{n'}$. As a result, Γ_n can be further improved.

On the other hand, the goal of the statements shown from lines 17 to 21 in Algorithm 1 is to prune the sensing responsibilities of s_n if it is better that these responsibilities are left for the neighbors with higher sensing efficiency. As defined above, δ^l_n is the sensing capability of u^l_n. The more $|\delta^l_n|$ is, the more targets u^l_n can cover at a time. Therefore, $|\delta^l_n|$ can be regarded as the *benefit* of u^l_n if u^l_n is turned on. On the contrary, e^l/E^r_n can be regarded as the *cost* of u^l_n, where e^l and E^r_n are the energy consumption of u^l in a time unit and the remaining energy of s_n, respectively. The cost considers not only the energy consumption of u^l, but also takes the remaining energy of s_n into account in order to reflect the effect of the energy consumption of u^l on the remaining energy of s_n. Consequently, $\frac{|\delta^l_n|}{e^l/E^r_n}$ can be regarded as the *benefit-cost ratio* (BCR) of u^l_n. In addition to BCR of u^l_n, the sensing efficiency of u^l_n on s_n should take the ratio of the remaining energy of s_n to the initial energy into consideration as well. Therefore, let $BCR(u^l_n)$ and $Eff(s_n, u^l)$ denote the BCR value of u^l_n and the sensing efficiency of u^l on s_n, respectively. Accordingly, the sensing efficiency of u^l on s_n, $Eff(s_n, u^l)$, is defined as $BCR(u^l_n) * (E^r_n/E)$, where $BCR(u^l_n) = \frac{|\delta^l_n|}{e^l/E^r_n}$. As a result, if there exists a sensor, say $s_{n'}$, who has not sent out the **DecAnn** packet and whose sensing efficiency of u^l on $s_{n'}$ is better than that of u^l on s_n, then s_n will leave the sensing responsibilities covered by u^l to $s_{n'}$. To do so can further alleviate the sensing responsibility of s_n.

The rest parts of EEFS please refer to Algorithm 1.

5 Performance Evaluations

In this section, the performance of the proposed schemes is evaluated via extensive simulations. The sensing field is of size $300m * 300m$. The number of sensors and the number of targets will be specified in each experiment. The locations of sensors and targets are not changed during the whole experiment. However, sensors are randomly deployed in the vicinity of the targets. The sensing range of each sensing unit is the same and is set as $50m$. The communication range of each sensor is twice of the sensing range. The initial energy of each sensor is 30 units. Without loss of generality, the energy consumption of each type of sensing unit is assumed linearly proportional to the types of sensing units. In the experiments, all measurements are averaged over 10 runs, if no otherwise notified. Energy consumption and network lifetime are evaluated to verify the performances of the proposed schemes. Energy spent in communication and computation is omitted. In addition, a reliable communication channel is also assumed. The IP

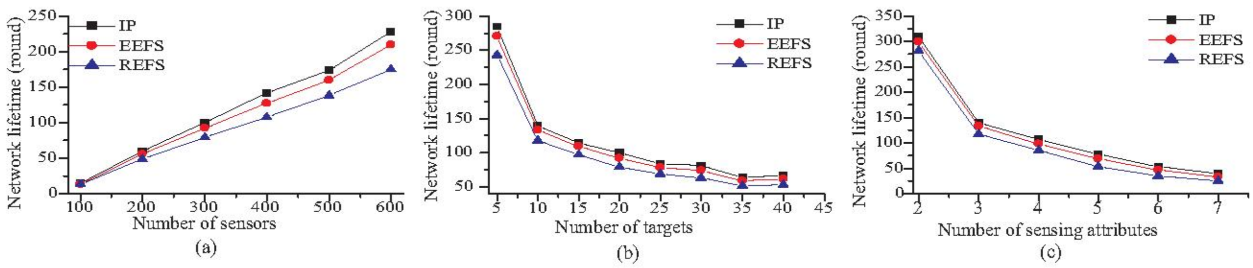

Figure 2. The impacts of the number of (a) sensors, (b) targets, and (c) attributes on the network lifetime.

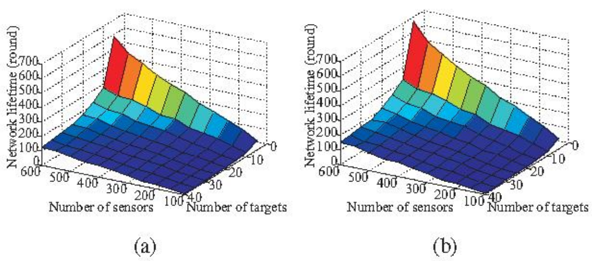

Figure 3. The impacts of the numbers of sensors and targets on the network lifetime in terms of (a) REFS and (b) EEFS.

solution is implemented by ILOG CPLEX [1] optimization library.

Firstly, the experiments are to observe *the impacts of the number of sensors*, in which the number of targets and the number of attributes are respectively fixed to 20 and 3, *the number of targets*, in which the number of sensors and the number of attributes are respectively fixed to 300 and 3, and *the number of attributes*, in which the number of targets and the number of attributes are respectively fixed to 20 and 3, on the network lifetime in terms of REFS, EEFS, and the IP solution. The results are shown in Figs. 2(a), (b), and (c), respectively. Clearly, IP solution has the longest network lifetime, whereas REFS has the shortest network lifetime in all cases. However, the difference between EEFS and the IP solution is small and is confined within 10%.

To observe the performances of REFS as well as EEFS comprehensively, the following experiments are made to evaluate the impact of the numbers of sensors and targets on the network lifetime. In the experiment, the number of attributes is fixed to 3. Figs. 3(a) and (b) illustrate the experimental results of REFS and EEFS, respectively. Both REFS and EEFS have similar inclination that the network lifetime increases with the increase of the number of sensors, but decreases with the increase of the number of targets. However, EEFS has better performance than REFS.

6 Conclusions

The paper emphasizes on the target coverage problem in wireless heterogeneous sensor networks with multiple sensing units, termed MUT problem. The problem is further reduced to a set cover problem, called MUST problem. According to the MUST problem, several IP (Integer Programming) constraints are proposed. Moreover, two distributed schemes, REFS and EEFS, are proposed to solve the MUT problem. Simulation results verify the advantages of the proposed schemes. It is worth mentioning that the difference between EEFS and the IP solution is confined within 10%, in terms of network lifetime.

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