# Integrating Target Coverage and Connectivity for Wireless Heterogeneous Sensor Networks with Multiple Sensing Units

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

## I. 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 [1], [2]. 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 [1], [2].

*Coverage* and *connectivity* are two key factors to the success of a WSN. The target coverage problem can be regarded as one of coverage problems. However, slightly different from the general coverage 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 [3]–[5]. In [3], the authors transformed the target coverage problem into a *maximal set cover problem*. The authors proposed a linear programming based heuristic algorithm and a centralized greedy algorithm. The target coverage problem considering adjustable sensing range was discussed in [4]. The authors used a bipartite graph to represent the coverage relation between sensors and targets. An LP-based heuristic, a centralized greedy, and a distributed greedy algorithms were proposed as well. On the other hand, the connectivity issue emphasizes on how the active sensors connect to the sink such that their sensing data can be delivered to the sink. The target coverage problem emphasizing on $k$-coverage and network connectivity was discussed in [5]. Although considering target coverage problem, the above papers only consider that each sensor equips with only one sensing unit. Moreover, some of them do not consider the connectivity issue.

The definition of the target coverage and connectivity problem in WHSNs with multiple sensing units, named MU-TCC (**M**ultiple Sensing **U**nits for **T**arget **C**overage and **C**onnectivity) problem, is given as follows.

*Definition 1 (MU-TCC Problem):* Given some targets and a number of sensors with multiple sensing units randomly deployed in area of interest, the MU-TCC problem is to schedule the on/off mode of sensors' sensing units and the communication module such that all the attributes at each target are continuously sensed, the sensing data can be delivered to the sink, and the network lifetime is maximized. □

The MU-TCC problem can be represented by a bipartite graph and be reduced to a connected set cover problem, named MU-CSC (**M**ultiple Sensing **U**nits for **C**onnected **S**et **C**over) problem. In [6], the connected set cover problem is shown as an NP-complete problem. Because the MU-CSC problem is a superset of the connected set cover problem, the MU-CSC problem is also an NP-complete problem. The MU-CSC 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 and connectivity problem in WHSNs with multiple sensing units. 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, redundant sensing is the most significant weakness of REFS. Therefore, 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 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, monitoring all targets with all sensing attributes, as well as maintaining the connectivity between sensors and the sink. From simulation results, both REFS and EEFS can prolong the network lifetime efficiently. To our best knowledge, this paper is the first one to discuss the target coverage and connectivity problem in WHSNs.

The rest of the paper is organized as follows. Section II explains the target coverage and connectivity problem and formulates the problem as IP constraints. In Section III, the distributed schemes, REFS and EEFS, are proposed to deal with the target coverage and connectivity problem. Simulation results are presented in Section IV. Section V concludes the paper.

## II. Problem Statements and IP Constraints

The paper assumes that sensors are randomly and stationarily deployed in the sensing field. 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 and the communication range of each sensor are assumed the same and are unadjustable. 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 assumes that $R_c \geq 2R_s$. The energy consumed by the communication module in a time unit is assumed the same. However, the energy consumed by different types of sensing units in a time unit is different. The initial energy of each sensor is assumed the same. Besides, each sensor can know its location and can obtain one-hop neighbor information via communication. Moreover, the locations of targets to be sensed are known by the 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.

### A. 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 sensing field.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 the corresponding purposes, if no otherwise specified.

- $m$: $m^{th}$ 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 $1 \leq l \leq L$.

Fig. 1 is an illustrated example. Fig. 1 (a) is the topology, where different circles mean the differences of sensing capabilities of sensors and the black solid lines represent the connectivity among sensors. Fig. 1 (b) illustrates the corresponding coverage and connectivity relationships in terms of sensing units and the communication module on the sensors, as well as the attributes at targets by means of a bipartite graph, where $u_n^l$ and $t_m^l$ 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

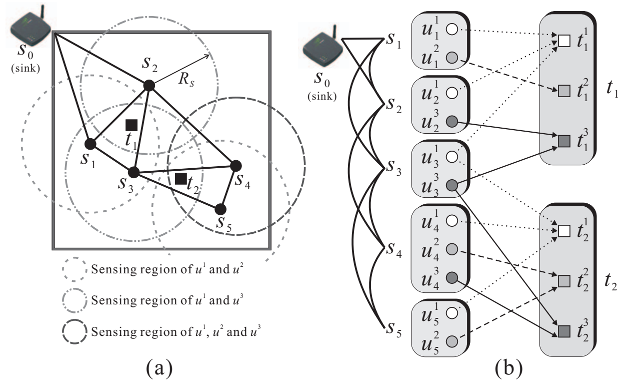



Fig. 1. An illustrated example: (a) the topology, (b) the coverage and connectivity relationships.

$u^l$ on sensor $s_n$ can sense the attribute $a^l$ at target $t_m$, there exists a ray from $u_n^l$ to $t_m^l$. In the figure, the different types of rays mean different types of sensing units. In addition, the black solid lines between two sensors means that these sensors can communicate with each other.

From the bipartite graph, the MU-TCC problem can be regarded as a connected set cover problem, termed MU-CSC problem in the paper. Sensors are organized as connected set covers. 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 $t_2$. Moreover, $s_1$, $s_3$, and $s_4$ can communicate with the sink via multi-hop transmission. Therefore, $\{u_1^2, u_3^1, u_3^3, u_4^2\}$ is a connected set cover. Formally, the MU-CSC problem is defined as follows.

*Definition 2 (MU-CSC Problem):* Given $M$ targets and $N$ sensors with multiple sensing units randomly deployed in area of interest, the MU-CSC problem is to find a family of connected 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 connected set cover, (3) the energy consumption of each sensor in all connected set covers is at most $E$, and (4) every sensor can deliver sensing data to the sink. □

Notice that, each connected set cover corresponds to a working period, say a *round*, for sensors and selected sensing units on these sensors. Thus, for the MU-CSC problem, maximizing $K$ is equal to maximize the network lifetime.

### B. IP Constraints for MU-CSC Problem

Before defining the IP constraints for the MU-CSC problem, some assumptions are made in the paper. Assume that a sensing unit of a sensor will transmit a unit of sensing data in a round. Every sensor has the responsibility to forward others' sensing data to the sink. In addition, the aggregation of sensing data is not considered here. Therefore, sensors nearby the sink have much heavier traffic than the others. By Definition 2, the MU-CSC problem can be formulated as integer programming (IP) constraints as follows.

**IP Constraints for the MU-CSC Problem**

*Given*:

- $M$ targets: $t_m, m = 1, 2, \ldots, M$,

- $N$ sensors: $s_n, n = 1, 2, \ldots, N$,
- The sink: $s_0$,
- 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: $e^l, l = 1, 2, \ldots, L$,
- $e_t$: the energy consumption of a sensor to transmit a unit of sensing data,
- $e_r$: the energy consumption of a sensor to receive a unit of sensing data,
- $\aleph(n) = \{n' | d(s_n, s_{n'}) \leq R_c, n' = 0, 1, ..., N, \forall n' \neq n\}$, where $d(s_n, s_{n'})$ is the Euclidean distance between $s_n$ and $s_i$.
- $u^l_{n,m}$: the coefficient indicates whether target $t_m$ can be sensed by sensor $s_n$ with the sensing unit $u^l$; $u^l_{n,m} = 1$ if sensor $s_n$ can use sensing unit $u^l$ to sense target $t_m$; otherwise, $u^l_{n,m} = 0$, $\forall\ m = 1, 2, \ldots, M$, $\forall\ n = 1, 2, \ldots, N$, and $\forall\ l = 1, 2, \ldots, L$.

*Variables*:

- $c_k$: boolean variable; $c_k = 1$ if $c_k$ is a connected set cover; otherwise, $c_k = 0$, $\forall\ k = 1, 2, \ldots, K$, where $K$ is an upper bound of the number of connected set covers,
- $\hat{u}^l_{n,k}$: boolean variable; $\hat{u}^l_{n,k} = 1$ if sensor $s_n$ enables the sensing unit $u^l$ in set $c_k$; otherwise, $\hat{u}^l_{n,k} = 0$, $\forall\ n, l, k$,
- $f_{nvk}$: the non-negative integer indicates the units of sensing data sent from $s_n$ to $s_v$ in set $c_k$. $s_n$ in set $c_k$ has to turn on its communication module to send or forward sensing data, if $\sum_{v \in \aleph(n)} (f_{nvk} + f_{vnk}) \neq 0$.

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

(C1) $\sum_{n=1}^{N} (u^l_{n,m} * \hat{u}^l_{n,k}) \geq c_k$, $\forall\ m, l, k$,
(C2) $\sum_{k=1}^{K} (\sum_{l=1}^{L} (\hat{u}^l_{n,k} * e^l) + e_t \sum_{v \in \aleph(n)} f_{nvk} + e_r \sum_{v \in \aleph(n)} f_{vnk}) \leq E$, $\forall\ n$,
(C3) $\hat{u}^l_{n,k} \leq c_k$, $\forall\ n, l, k$,
(C4) $\sum_{v \in \aleph(n)} f_{nvk} - \sum_{v \in \aleph(n)} f_{vnk} = \sum_{l=1}^{L} \hat{u}^l_{n,k}$, $\forall n, k$,
(C5) $\sum_{n \in \aleph(0)} f_{n0k} = \sum_{n=1}^{N} \sum_{l=1}^{L} \hat{u}^l_{n,k}$, $\forall k$,
(C6) $\hat{u}^l_{n,k} \in \{0, 1\}$, $\forall\ n, l, k$,
(C7) $c_k \in \{0, 1\}$, $\forall\ k$.
(C8) $f_{nvk} \in \{0, 1, 2, ..., N \cdot L\}$, $\forall\ n, v, k$.

Constraints (C1), (C2) and (C5) respectively correspond to the second, the third and the fourth requirements in Definition 2. Constrain (C3) makes sure that a sensor does not turn on its sensing units if the sensor belongs to a non-connected set cover. Constraint (C4) ensures that the sensing data of a sensor can be forwarded by the other sensors.

## III. Distributed Schemes for the MU-TCC Problem

Two distributed schemes, named REFS (Remaining Energy First Scheme) and EEFS (Energy Efficient First Scheme), are proposed to solve the MU-TCC problem, where time is divided into rounds of equal period. Each round is further divided into an *initial phase* and a *working phase*. The initial phase consists the *sensing and relaying subphase* (SAR) and the *pure relaying subphase* (PR). During SAR, each sensor determines which sensing units should be turned on in the following working phase and whether it should relay data for other sensors. During PR, a sensors only has to determine whether it should relay data for other sensors. In addition, each sensor makes the decision only through one-hop neighbor information, including the location, the remaining energy, and the sensing capability of neighbors, as well as the requests for the relaying.

### *A. Remaining Energy First Scheme (REFS)*

REFS is a greedy approach, which takes the sensor's remaining energy and neighbors' decisions into account to enable its sensing units and communication module. Algorithm 1 illustrates the details of REFS.

Let $\delta^l_n$ be the sensing capability of the sensing unit $u^l$ on sensor $s_n$, if sensor $s_n$ is equipped with $u^l$. Consequently, $\delta^l_n = \{t^l_m | d(t_m, s_n) \leq R_s, \forall\ m\}$. Furthermore, let $\Delta_n$ 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, $\Delta_n = \{\delta^l_n | \forall\ u^l_n\}$.

REFS is a self-pruning approach. Initially, a sensor, say $s_n$, will take all $t^l_m$ that it can sense as its sensing responsibility. Let $\Gamma_n$ denote the *sensing responsibility* of $s_n$. At the beginning of an initial phase of each round, $\Gamma_n$ is initialized to $\bigcup_{\forall u^l_n} \delta^l_n$. For the example shown in Fig. 1, $\Gamma_1 = \delta^1_1 \cup \delta^2_1 = \{t^1_1, t^2_1\}$ and $\Gamma_3 = \delta^1_3 \cup \delta^3_3 = \{t^1_1, t^1_2, t^3_1, t^3_2\}$. 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 $\Gamma_n$ 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 $W$, $W_{SAR}$, and $W_{PR}$ respectively denote the duration of a initial phase, a SAR and a PR. Clearly, $W = W_{SAR} + W_{PR}$. Note that $W$ is much less than the duration of a round. In addition, let $W_n$ denote the waiting time of sensor $s_n$ and $E^r_n$ stand for the remaining energy of sensor $s_n$, for $n = 1, 2, \ldots, N$. Thus, $W_n$ can be set as $(1 - \frac{E^r_n}{E}) * W_{SAR}$, $n = 1, 2, \ldots, N$. During $W_n$, $s_n$ prunes out those $t^l_m$ revealed in the decision packet from its sensing responsibility once receiving neighbor's decision packet.

Upon $W_n$ expired, the remaining $\Gamma_n$ 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 $\Gamma_n$ to operate during the whole working phase. As a result, $s_n$ will orderly remove the sensing unit whose sensing capability is the weakest. That is, the number of targets that the sensing unit can sense is the smallest, as shown in line 12 in Algorithm 1.

Finally, $s_n$ enables the corresponding sensing units indicated in the remaining $\Gamma_n$. Once deciding to turn the sensing units, $s_n$ selects the neighbor $s_{n'}$ whose distance to the sink is the smallest among the neighbors of $s_{n'}$. Let $w_{n'}$ be set as $1/d(s_{n'}, s_0), \forall n' \in \aleph(n)$, where $s_0$ is the sink. Formally, for $s_n$, $s_{n'}|_{\max_{n'}(w_{n'}), \forall\ n' \in \aleph(n)}$ will be selected as the relay. The selected relay also has to find another relay if the relay does

**Algorithm 1**: Remaining Energy First Scheme (REFS)

/* To be performed by each sensor in a distributed fashion. Suppose the sensor performed is $s_n$. */
**Input**: $\Delta_n = \{\delta_n^l | \forall\, u_n^l\}$ // Sensing capability of $s_n$.
**Result**: Decide $\Gamma_n$ and broadcast a **DecAnn** packet.
1 **begin**
2 $\Gamma_n = \bigcup_{\forall u_n^l} \delta_n^l$ ; // Initialize the sensing responsibility $\Gamma_n$.
3 $isRelay = false$ ; // Initialize $s_n$ to a non-relay node.
4 $W_n = (1 - \frac{E_n^r}{E}) * W_{SAR}$ ; // Set the waiting time.
5 **while** *$W_n$ is not expired* **do**
6 **if** **DecAnn** *packet is received, say from $s_{n'}$* **then**
7 $\Gamma_n = \Gamma_n - \Gamma_{n'}$ ; // Remove redundant sensing responsibilities.
8 **if** *$s_n$ is the relay node of $s_{n'}$* **then**
9 $isRelay = true$ ;
10 **if** $\Gamma_n \neq \emptyset$ **or** $isRelay$ **then**
11 **while** $\sum_{l|_{t_m^l \in \Gamma_n}} e^l \geq E_n^r$ **do** // $s_n$'s remaining energy is not enough to support the required sensing responsibilities.
12 $\Gamma_n = \Gamma_n - \{t_m^{l'} \in \Gamma_n, \forall\, m \mid l' = l|_{\min_l |\{t_m^l, \forall\, m | t_m^l \in \Gamma_n\}|}\}$ ; // Remove the sensing responsibility with the smallest capability.
13 Enable all sensing units $u^l$, if $t_m^l \in \Gamma_n$ ;
14 $nextRelay = s_{n'}|_{\max_{n'}(w_{n'}), \forall\, n'}$ ;
15 Pack **DecAnn** packet to include $\Gamma_n$ and $nextRelay$ ;
16 Broadcast **DecAnn** packet ;
17 **while** *$W$ is not expired* **do**
18 **if** *received* **DecAnn** *packet* **and** *is specified as a relay* **and** *has not selected $nextRelay$* **then**
19 $nextRelay = s_{n'}|_{\max_{n'}(w_{n'}), \forall\, n'}$ ;
20 Pack **DecAnn** packet to include $nextRelay$ ;
21 Broadcast **DecAnn** packet ;
22 **end**

not directly connect to the sink. Similarly, $s_n$ also announces its decision and the selected relay by sending out a **DecAnn** packet. When receiving any request for relaying before the end of the initial phase, including the remaining part of $W_{SAR}$ and the whole $W_{PR}$, the sensor will be a relay and follows the similar procedure, as shown in lines 10–21 in Algorithm 1, to find its relay.

Note that, if sensor $s_n$ has no enough energy to enable any sensing unit, it stops executing REFS and turns off all the sensing units. The remaining energy of $s_n$ will leave for communication, not for sensing.

### *B. Energy Efficient First Scheme (EEFS)*

EEFS is also a self-pruning approach. EEFS is operated at the initial phase by each sensor to distributively decide the on/off mode of each sensing unit and the communication module 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.

Before executing EEFS, each sensor has to collect its and neighbors' sensing capabilities and critical sensing responsi-

**Algorithm 2**: 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 $\Gamma_n$ and broadcast a **DecAnn** packet.
1 **begin**
2 Exchange $E_n^r$ with neighbors ;
3 $\Gamma_n = \bigcup_{\forall u_n^l} \delta_n^l$ ;
4 $isRelay = false$ ;
5 **foreach** $u_n^l$ **do**
6 $\mathcal{L}$ = 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 ;
7 $r_n^l$ = the order of $\delta_n^l$ in the list $\mathcal{L}$ ;
8 $r_{max}^l = |\mathcal{L}|$ ;
9 $\rho_n = \sum_{\forall u_n^l} \frac{r_n^l}{r_{max}^l}$ ;
10 $W_n = (1 - \alpha * \frac{E_n^r}{E} * \frac{\rho_n}{|\{u_n^l\}|} - (1-\alpha) * \prod_{n' \in \aleph(n)} \frac{d(s_n, s_0) - d(s_{n'}, s_0) + R_c}{2 * R_c}) * W_{SAR}$ ;
11 **while** *$W_n$ is not expired* **do**
12 **if** **DecAnn** *packet is received, say from $s_{n'}$* **then**
13 $\Gamma_n = \Gamma_n - \Gamma_{n'}$ ;
14 **if** *$s_n$ is the relay of $s_{n'}$* **then**
15 $isRelay = true$ ;
16 **foreach** $u_n^l$ **do**
17 **foreach** $n' \in \aleph(n)$ **do**
18 **if** $\delta_{n'}^l \cap \Theta_{n'} \neq \emptyset$ **then**
19 $\Gamma_n = \Gamma_n - \delta_{n'}^l$ ;
20 **foreach** $t_m^l \in \Gamma_n$ **do**
21 **foreach** $n' \in \aleph(n)$ **do**
22 **if** *$s_{n'}$'s* **DecAnn** *packet is not received* **and** $Eff(s_{n'}, u^l) > Eff(s_n, u^l)$ **then**
23 $\Gamma_n = \Gamma_n - \{t_m^l\}$ ;
24 **break** ;
25 The rest parts are the same as the parts in Algorithm 1 from the line 10 to the line 21 ;
26 **end**

bilities in advance to efficiently make use of the sensing units and communication module 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 $\Theta_n$ 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 $\Delta_n$ and $\Theta_n$ as well as to collect $\Delta_{n'}$ and $\Theta_{n'}, \forall\, n' \in \aleph(n)$.

At the beginning of EEFS, each sensor has to exchange $E_n^r$ with its neighbors. In addition, $s_n$ has to rank its sensing priority among its neighbors to decide $W_n$ to let the sensor with more remaining energy, higher priority of sensing units, and lower probability of being others relay make the decision earlier. The ranking is processed as follows. If $s_n$ equips with the sensing unit $u^l$, $s_n$ will sort $\delta_{n'}^l$ to a list $L$ according to $|\delta_{n'}^l|, \forall\, n' \in \{n\} \cup \aleph(n)$ 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 $r_n^l$ be the order in the sorted list, which means the priority of $s_n$'s sensing unit $u^l$ among its neighbors. The larger the $r_n^l$ is, the higher its priority is. Moreover, let $r_{max}^l$ 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. Let $\rho_n$ be the priority of $s_n$, which takes the priorities of all sensing units equipped on $s_n$ into consideration. $\rho_n$ is set as $\sum_{\forall u_n^l} r_n^l / r_{max}^l$. For the above example, $\rho_1 = \frac{1}{3} + \frac{1}{1} = \frac{4}{3}$.

Therefore, $W_n$ can be set as $(1 - \alpha * \frac{E_n^r}{E} * \frac{\rho_n}{|\{u_n^l\}|} - (1-\alpha) * \prod_{n' \in \aleph(n)} \frac{d(s_n,s_0) - d(s_{n'},s_0) + R_c}{2*R_c}) * W_{SAR}$. $\frac{\rho_n}{|\{u_n^l\}|}$ is an average priority of sensing units equipped on $s_n$, and therefore, considers the *coverage contribution* of $s_n$. Notice that $0 < \rho_n / |\{u_n^l\}| \leq 1$. With regard to the example in Fig. 1, $\rho_1 / |\{u_1^l\}| = \frac{4}{3}/2 = \frac{2}{3}$. On the other hand, $\prod_{n' \in \aleph(n)} \frac{d(s_n,s_0) - d(s_{n'},s_0) + R_c}{2*R_c}$ is the probability that $s_n$ will not be others' relay. In order not to increase the communication overhead, only the distance between $s_n$ and $s_0$ as well as the distance between $s_{n'}$ and $s_0$ are used to determine the probability. The higher the probability is, the farther $s_n$ to the sink is. Therefore, $s_n$ has lower probability to be a relay and can have much energy to perform the sensing tasks. Consequently, the probability considers the *connectivity contribution* of $s_n$. $\alpha$ is an adjustable parameter to determine the relative weight of coverage and connectivity contributions of $s_n$.

Then, the following statements from line 11 to line 15 are the same as those in REFS from line 5 to line 9, respectively. The goal of these statements is to prune the redundant $t_m^l$ which has been decided to be covered by the neighbors indicated from their **DecAnn** packets. Upon the expiration of $W_n$, the remaining $\Gamma_n$ 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 16 to 19 in Algorithm 2 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 $t_m^l$ ($\in \Theta_{n'}$), for some $m$, turning on the sensing unit is also possible to cover the other targets, say $t_{m'}^l$, for some $m'$. That is, $t_{m'}^l \in \delta_{n'}^l$. Therefore, if $t_{m'}^l \in \Gamma_n$, $t_{m'}^l$ can be pruned from $\Gamma_n$ since $t_{m'}^l$ must be covered by $s_{n'}$. As a result, $\Gamma_n$ can be further improved.

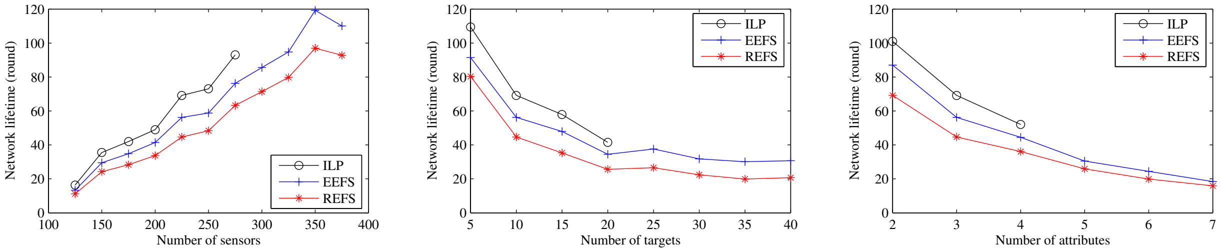
On the other hand, the goal of the statements shown from lines 20 to 24 in Algorithm 2 is to prune the sensing responsibilities of $s_n$ if it is better that these responsibilities are left for the neighbors with higher sensing efficiency. As defined above, $\delta_n^l$ is the sensing capability of $u_n^l$. The more $|\delta_n^l|$ is, the more targets $u_n^l$ can cover at a time. Therefore, $|\delta_n^l|$ can be regarded as the *benefit* of $u_n^l$ if $u_n^l$ is turned on. On the contrary, $\frac{e^l}{E_n^r}$ can be regarded as the *cost* of $u_n^l$, where $e^l$ and $E_n^r$ 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, $\frac{|\delta_n^l|}{e^l/E_n^r}$ can be regarded as the *benefit-cost ratio* (BCR) of $u_n^l$. In addition to BCR of $u_n^l$, the sensing efficiency of $u_n^l$ on $s_n$ should take the ratio of the remaining energy of $s_n$ to the initial energy into consideration as well. Therefore, let $BCR(u_n^l)$ and $Eff(s_n, u^l)$ denote the BCR value of $u_n^l$ 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 $BCR(u_n^l) * \frac{E_n^r}{E}$, where $BCR(u_n^l) = \frac{|\delta_n^l|}{e^l/E_n^r}$. 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 rests part of EEFS are similar to those in REFS and are to determine the relay of $s_n$ according to the weight of neighbors. Let $w_{n'}$ be the weight of $s_{n'}$, $\forall n' \in \aleph(n)$. When the remaining energy and the distance to the sink are taken into account, $w_{n'}$ can be obtained by $\frac{E_{n'}^r}{E} * [1 - \frac{d(n',s_0)}{\max_{j \in \aleph(n)} d(s_n,s_j)}]$. However, in order to use sensors' energy efficiently, the neighbor whose $w_{n'}$ is the largest and whose sensing capability is empty ($\triangle = \{\emptyset\}$) will be the relay of $s_n$. Otherwise, if $\triangle_{n'} \neq \{\emptyset\}, \forall n' \in \aleph(n)$ , $s_n$ only selects $s_{n'}|_{\max_{n'}(w_{n'}), \forall\ n' \in \aleph(n)}$ as the relay. Without loss of generality, $w_{n'}$ is modified as $\frac{E_{n'}^r}{E} * [1 - \frac{d(s_{n'},s_0)}{\max_{j \in \aleph(n)} d(s_j,s_0)}] + 1$, if $\triangle_{n'} = \{\emptyset\}$.

## IV. Performance Evaluations

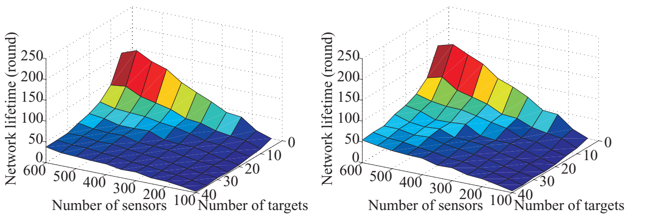
The performance of the proposed schemes is evaluated via extensive simulations. The sensing field is of size $300m * 300m$. The number of sensors and the number of targets are specified in each experiment. The locations of sensors and targets are not changed during the whole experiment. However, sensors are randomly deployed in the sensing field. 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 50 units. Due to the space limitation, the impact of the adjustable parameter $\alpha$ on the network lifetime is omitted. For simplicity, $\alpha$ is set as 0.5 for all the simulations. Without loss of generality, the energy consumption of each type of sensing unit is assumed linearly proportional to the types of sensing units. Additionally, the communication module of a sensor consume one unit of energy to send or receive a unit of sensing data. In the simulations, all measurements are averaged over 10 runs.

Energy consumption and network lifetime are evaluated to verify the performance of the proposed schemes. Network lifetime is measured in terms of the number of rounds that all attributes on each target can be sensed completely from the




(a) (b) (c)

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




(a) (b)

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

beginning until the first loss of coverage of any attribute on any target in the network. Moreover, the energy consumption only takes that spent in sensing into account. Energy spent in computation is omitted. The IP solution is implemented by ILOG CPLEX [7] optimization library.

Firstly, the simulations 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 10 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 10 and 3, on the network lifetime in terms of REFS, EEFS, and IP solution. The results are respectively shown in Figs. 2(a), 2(b), and 2(c). Because the IP solution can not be obtained from the IP solver when too many attributes, targets, or sensors are involved in the simulation, partial results of the IP solution are obtained and shown in Fig. 2. Clearly, the IP solution has the longest network lifetime, whereas REFS has the shortest network lifetime in all cases. However, the curves of the IP solution and the proposed protocols in Fig. 2 have similar inclination. Therefore, the proposed protocols are practical to be implemented in WHSNs because the proposed protocols are distributed, whereas the IP solution is centralized and needs high computation cost.

To observe the performance of REFS as well as EEFS comprehensively, the following simulations are made to evaluate the impact of the numbers of sensors and targets on the network lifetime as shown in Fig. 3. In the simulations, the number of attributes is fixed to 3. Fig. 3(a) and Fig. 3(b) illustrate the simulation 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, the EEFS has better performance than REFS.

## V. Conclusions

The paper emphasizes on the target coverage and connectivity problem in wireless heterogeneous sensor networks with multiple sensing units, termed MU-TCC problem. The problem is further reduced to a connected set cover problem, called MU-CSC problem. According to the MU-CSC problem, several IP constraints are proposed. In addition, two distributed schemes, REFS and EEFS, are proposed to solve the MU-TCC problem. Simulation results show that REFS and EEFS can prolong the network lifetime effectively. The performances of the schemes are close to that of the IP solution. However, the IP solution is a centralized and computation-intensive scheme, so the proposed distributed schemes are much practical. In addition, the schemes are easy implemented in a real network.

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