# Prolonging Network Lifetime for Target Coverage in Sensor Networks

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**Abstract.** Target coverage is a fundamental problem in sensor networks for environment monitoring and surveillance purposes. To prolong the network lifetime, a typical approach is to partition the sensors in a network for target monitoring into several disjoint subsets such that each subset can cover all the targets. Thus, each time only the sensors in one of such subsets are activated. It recently has been shown that the network lifetime can be further extended through the overlapping among these subsets. Unlike most of the existing work in which either the subsets were disjoint or the sensors in a subset were disconnected, in this paper we consider both target coverage and sensor connectivity by partitioning an entire lifetime of a sensor into several equal intervals and allowing the sensor to be contained by several subsets to maximize the network lifetime. We first analyze the energy consumption of sensors in a Steiner tree rooted at the base station and spanning the sensors in a subset. We then propose a novel heuristic algorithm for the target coverage problem, which takes into account both residual energy and coverage ability of sensors. We finally conduct experiments by simulation to evaluate the performance of the proposed algorithm by varying the number of intervals of sensor lifetime and network connectivity. The experimental results show that the network lifetime delivered by the proposed algorithm is further prolonged with the increase of the number of intervals and improvement of network connectivity.

## 1 Introduction

Recent advances in microelectronic technology have made it possible to construct compact and inexpensive wireless sensors. Networks consisting of sensors have received significant attention due to their potential applications from civil to military domains [1]. The main constraint of sensors however is their low finite battery energy, which limits the network lifetime and impairs the network quality. To prolong the network lifetime, energy-efficiency in the design of sensor network protocols is thus of paramount importance.

In this paper, we consider a sensor network used for monitoring targets. One efficient method of reducing the energy consumption of sensors and thereby prolonging the network lifetime is to partition the sensors in the network into multiple subsets (sensor covers) such that each subset can cover all the targets.

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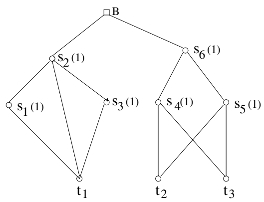
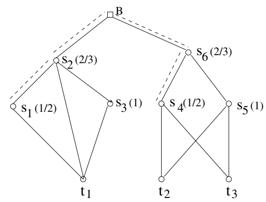
Thus, each time only one sensor cover is activated for a certain period and only the sensors in the active sensor cover are in active mode, while all the other sensors are in sleep mode to save energy. Meanwhile, the communication subgraph induced by the base station and the active sensors must be connected so that the sensed data can be collected at the base station for further processing. Although most of the existing work related to target coverage mainly focused on finding disjoint sensor covers, Cardi *et al* [2] recently presented a novel approach that allows sensor covers not to be disjoint, i.e., a sensor can be included in up to $p$ sensor covers, where $p \geq 1$. Thus, sensor lifetime is partitioned into $p$ equal intervals and each interval corresponds to the duration of the sensor in the active sensor cover. The network lifetime is then the sum of the duration of the sensor covers that can be found in the network. They showed that the network lifetime can be further prolonged by allowing the overlapping among sensor covers. However, they only considered target coverage but sensor connectivity in a sensor cover was not considered.

While taking both target coverage and sensor connectivity into consideration, the energy consumption among the sensors will not be identical, because some sensors consume more energy on both sensing and transmission, whereas the others consume energy on transmission only. This imbalance on energy consumption may result in the situation where no further sensor covers exist but the total residual energy among the sensors in the network is still quite high. For example, consider a network consisting of the base station $B$, sensors $s_1, s_2, s_3, s_4, s_5, s_6$ and targets $t_1, t_2, t_3$ (see Fig. 1(a)). Assume that $p$ is 2, both the initial energy capacity and sensor lifetime are 1 units, and each sensor consumes 1/3 and 2/3 units of energy for sensing and transmitting data for 1 time unit. A collection of connected sensor covers will be built until there are no further connected sensor covers, where each sensor cover can last at least $1/p$ time units. To built a connected sensor cover, a sensor cover is found first, followed by the construction of a Steiner tree rooted at the base station and spanning the sensors in the cover. The Steiner trees are activated successively and each tree lasts 1/2 time units. Thus, a terminal node and a non-terminal node in a Steiner tree consume $(1/3 + 2/3) * 1/2 = 1/2$ and $2/3 * 1/2 = 1/3$ units of energy, respectively. In Fig. 1, the trees with dotted edges are the Steiner trees and the values in the brackets are the residual energies of sensors after the trees last 1/2 time units.

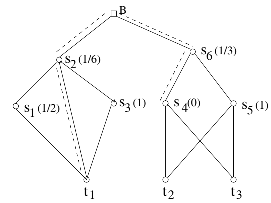
A sensor cover $\mathcal{C}_1 = \{s_1, s_4\}$ can be found and the correspondent Steiner tree is built for data transmission (see Fig. 1(b)). If $\mathcal{C}_2 = \{s_2, s_4\}$ is chosen as a sensor cover after the tree in Fig. 1(b) lasts 1/2 time units, then no further Steiner trees lasting 1/2 time units can be found for transmitting the sensed data for target $t_1$ to the base station, since the sensed data for target $t_1$ has to be transferred to the base station through sensor $s_2$ but $s_2$ has no sufficient residual energy for 1/2 time units transmission (see Fig. 1(c)). Thus, the network lifetime is 1 time unit since only two connected sensor covers can be found, and the total residual energy left in the network are 3 units. However, we can see that the network lifetime can be further prolonged by balancing residual energy among sensors. One such approach is to include sensors with high residual energy



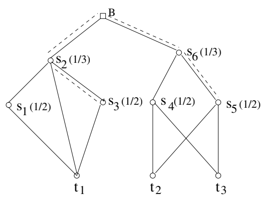

(a) A sensor network



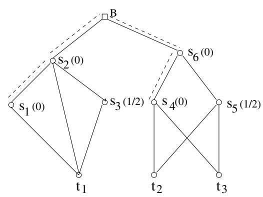

(b) $\mathcal{C}_1 = \{s_1, s_4\}$




(c) $\mathcal{C}_2 = \{s_2, s_4\}$




(d) $\mathcal{C}_3 = \{s_3, s_5\}$




(e) $\mathcal{C}_4 = \{s_1, s_4\}$

**Fig. 1.** An example for balancing the residual energy among sensors

into sensor covers. Then, there are the other two sensor covers $\mathcal{C}_3 = \{s_3, s_5\}$ and $\mathcal{C}_4 = \{s_1, s_4\}$ (see Fig. 1(d) and (e)) after the tree in Fig. 1(b) has been activated for 1/2 time units. The network lifetime is thus extended to 1.5 time units and the total residual energy of the sensors is only 1 unit (see Fig. 1(e)).

Motivated by the above example and the work of Cardi *et al* in [2], we here consider both target coverage and sensor connectivity by partitioning sensor lifetime into several equal intervals and allowing a sensor to be contained by more than one sensor cover. However, there are several essential differences between theirs and ours. (i) They only focused on target coverage and whether or not the communication subgraph induced by a sensor cover is connected has not been taken into account, while we consider both target coverage and sensor connectivity. (ii) They only considered the energy consumption on data sensing, and assume that all the sensors in a sensor cover consume the same amount of energy. Such an assumption is reasonable for the case where sensor connectivity is not considered. In practice, this assumption however is inapplicable, because the energy required for data transmission usually is one order of magnitude greater than that for data sensing. Thus constructing a connected sensor cover is challenging, which depends on not only the current coverage ability but also the residual energy of sensors that would not be known in advance. It is crucial to balance the energy consumption on sensing and transmission among the sensors while constructing a connected sensor cover. In this paper, we assume that the data transmission is message-length independent, i.e., each sensor transmits the same volume of data to its parent no matter how much data it received from its children, and both sensed data and transmitted data are a unit-length.

**Related work.** In recent years, tremendous effort on network lifetime maximization and energy efficiency has been taken for target coverage, sensor connectivity and network fault toleration [3]-[13]. For example, Cardei *et al* [3] dealt with the target coverage problem by organizing sensors into disjoint sensor covers, and allowing only one of the covers to be activated at any given time. The network lifetime is then prolonged through the maximization of the number of sensor covers. Chakrabarty *et al* [4] studied the problem by employing grid coverage and presenting an integer linear programming solution. Wang *et al* [5] investigated the problem by adopting two methods (disk coverage and sector coverage) to explore the sensor density required for guaranteeing a localization error bound over the sensing field. Dong *et al* [6] considered load balancing while guaranteeing that each target is monitored by at least one sensor with an objective to minimizing the maximum energy consumption of sensors for its targets, and proposed centralized and distributed algorithms for it. Cai *et al* [7] studied the problem of multiple directional sensor covers by proving its NP-completeness, followed by proposing heuristic solutions. Wang *et al* [8] studied the target coverage problem by proposing a randomized algorithm, which takes much less time than that of the algorithms in [7]. The connected target coverage problem is considered in [9,10]. Jaggi *et al* [9] proposed an algorithm by decomposing the set of sensors into disjoint subsets such that each subset can guarantee target coverage and sensor connectivity, and their algorithm was within a constant factor of the optimum. Lu *et al* [10] addressed the problem through the adjustment of sensing ranges of sensors and devised a distributed algorithm to determine the sensor range of each individual sensor. By taking routing robustness into account, Li *et al* [11] considered the $k$-connected target coverage problem by showing its NP-hardness, and they instead designed two heuristic algorithms for the problem. Zhou *et al* [12] introduced the $k_1$-connected, $k_2$-cover problem, and proposed a distributed algorithm for the problem by inactivating all the other sensors that are not in the active sensor cover.

## 2 Preliminaries

**System model.** A wireless sensor network consisting of $n_s$ homogeneous sensors that are randomly deployed in a region of interest to monitor $n_t$ targets is modelled by an *undirected graph* $G(V,E)$, where $V = V_S \cup V_T$ and $E = E_S \cup E_T$. $V_S$ is the set of sensors and $V_T$ is the set of targets with $|V_S| = n_s$ and $|V_T| = n_t$, and $E_S$ is the set of edges between sensors and $E_T$ is the set of edges between sensors and targets. For each pair of sensors $s_i$ and $s_j$, there is an edge $(s_i, s_j)$ in $E_S$ if and only if they are within the *transmission range* $r_t$ of each other. For each pair of sensor $s$ and target $t$, there is an edge $(s,t)$ in $E_T$ if and only if $t$ is within the *sensing range* $r_s$ of $s$. *A sensor cover* is a set of sensors that can cover all the targets. *A connected sensor cover* is a sensor cover such that the subgraph induced by the base station and the sensors in the cover is connected. *The lifetime of a sensor cover* is the time at which the first sensor in the cover fails due to its energy expiration. *The lifetime of a Steiner tree* is the time when its first node fails. *A sensor cover with lifetime threshold* $\delta$ is such a sensor cover that its lifetime is at least $\delta$ time units, and similarly *a Steiner tree with lifetime threshold* $\delta$ is such a Steiner tree that its lifetime is at least $\delta$ time units, where

$\delta > 0$. We assume that each sensor has identical initial energy capacity $IE$, and $e_s$ and $e_t$ are the energy consumptions for sensing and transmitting a unit-length data respectively, then a sensor can last at least $\tau = IE/(e_s + e_t)$ time units. We further assume that a sensor can participate in at most $p$ sensor covers. Without loss of generality, $\tau$ and $p$ are referred to as *sensor lifetime* and *lifetime granularity*, respectively. Thus, the sensor lifetime of a sensor is partitioned into $p$ intervals, and each interval corresponds to the duration of the corresponding sensor cover in which the sensor belongs to.

**Problem definition.** Given a sensor network $G(V, E)$ consisting of sensors and targets, *the target coverage problem* is to find a collection of connected sensor covers such that the sum of the lifetimes of these sensor covers is maximized. Note that it is not necessary that sensor covers be disjoint, which means that there may exist overlapping between two sensor covers.

## 3 Algorithm for Target Coverage Problem

In this section, we first provide an overview of the algorithm for the target coverage problem. We then explore the energy consumption of sensors in a Steiner tree corresponding to a connected sensor cover. We finally present a heuristic algorithm for the problem of concern.

**Overview of the algorithm.** For a given sensor network $G(V, E)$, lifetime granularity $p$ and sensor lifetime $\tau$, we construct a collection $\{\mathcal{C}_1, \mathcal{C}_2, \cdots, \mathcal{C}_q\}$ of connected sensor covers such that the lifetime of each sensor cover is at least $\delta$ time units with an objective to maximizing the network lifetime $\delta * q$, where $p \geq 1$, $\delta (= \tau/p)$ is referred to as *lifetime threshold* and $q \geq 0$. Note that each sensor cover is activated for $\delta$ time units in order to allow a sensor to participate in more than one sensor cover.

The proposed algorithm proceeds iteratively as follows. The network lifetime is set to be zero initially. Within each iteration, if there is a connected sensor cover with lifetime threshold $\delta$, then the network lifetime increases by $\delta$ time units. The construction of a connected sensor cover consists of two phases. Phase one is to find a sensor cover, and phase two is to construct a Steiner tree $\mathtt{T}'$ of a directed, edge-weighed auxiliary graph $G'$ rooted at the base station and spanning the sensors in the sensor cover, where the lifetimes of both the sensor cover and the Steiner tree are at least $\delta$ time units. A Steiner tree $\mathtt{T}$ of $G$ is derived from $\mathtt{T}'$. The residual energy of the sensors in $\mathtt{T}$ is updated after $\mathtt{T}$ lasts $\delta$ time units. The algorithm continues until there are no further connected sensor covers with lifetime threshold $\delta$ in the network.

**Energy consumption of the sensors in a routing tree.** Since the construction of a connected sensor cover depends on the current network status including the residual energy of sensors, we now explore the energy consumption of sensors in a Steiner tree corresponding a connected sensor cover. To guarantee that the lifetime of a Steiner tree is at least $\delta$ time units, only those sensors with sufficient residual energy for $\delta$ time units sensing and transmission can be included in the tree as terminal nodes, and only the sensors with sufficient residual energy for $\delta$

time units transmission can be included in the tree as non-terminal nodes. Let $\gamma = e_t/e_s$ be the ratio of the transmission energy consumption $e_t$ to the sensing energy consumption $e_s$ for a unit-length data, and $\theta(v) = U(v)/IE$ the energy utility ratio of sensor $v$, which is the ratio of the consumed energy $U(v)$ of $v$ to the initial energy capacity $IE$. The introduction of $\gamma$ and $\theta$ significantly simply the assumption related to the energy of sensors, and the following lemma shows the judgement on whether a sensor in the network has sufficient residual energy for $\delta$ time units sensing and/or transmission can be reduced to a proposition related only to $\gamma$ and $\theta$, and the updating of residual energy of sensors in a Steiner tree can be reduced to the updating of $\theta$.

**Lemma 1.** *Given a sensor network $G(V, E)$, lifetime granularity $p$ and sensor lifetime $\tau$, assume that $\mathcal{C}$ is a sensor cover with lifetime threshold $\delta$, and* T *is a Steiner tree with lifetime threshold $\delta$ rooted at the base station and spanning the sensors in $\mathcal{C}$, where $\delta = \tau/p$. Let $U(v)$ and $U'(v)$ be the consumed energy of sensor $v$ before and after* T *last $\delta$ time units data sensing and transmission. $\theta(v) = U(v)/IE$, $\theta'(v) = U'(v)/IE$, and $\gamma = e_t/e_s$. If $v$ is a terminal node in tree* T*, then $1 - \theta(v) \geq \frac{1}{p}$, and $\theta'(v) = \theta(v) + \frac{1}{p}$; Otherwise, $1 - \theta(v) \geq \frac{1}{p*(1+\frac{1}{\gamma})}$, and $\theta'(v) = \theta(v) + \frac{1}{p*(1+\frac{1}{\gamma})}$.*

*Proof.* If $v$ is a terminal node in T, then $v$ is in sensor cover $\mathcal{C}$, and $v$ serves for both sensing and transmission for $\delta$ time units. The energy consumption of $v$ is

$$\delta * (e_s + e_t) = \frac{\tau}{p} * (e_s + e_t) = \frac{\frac{IE}{e_s+e_t}}{p} * (e_s + e_t) = \frac{IE}{p}.$$

Since the lifetime of T is at least $\delta$ time units, the residual energy of sensor $v$ is no less than the amount of energy $\frac{IE}{p}$, i.e. $IE - U(v) \geq \frac{IE}{p}$. Then, we have

$$1 - \theta(v) = 1 - \frac{U(v)}{IE} = \frac{IE-U(v)}{IE} \geq \frac{1}{p},$$

and

$$\theta'(v) = \frac{U'(v)}{IE} = \frac{U(v)+\frac{IE}{p}}{IE} = \frac{IE*\theta(v)+\frac{IE}{p}}{IE} = \theta(v) + \frac{1}{p}.$$

Otherwise, sensor $v$ in T serves only for transmitting data from its children to its parent for $\delta$ time units. The transmission energy consumption of $v$ is

$$\delta * e_t = \frac{\tau}{p} * e_t = \frac{\frac{IE}{e_s+e_t}}{p} * e_t = \frac{IE}{p*(1+\frac{e_s}{e_t})} = \frac{IE}{p*(1+\frac{1}{\gamma})}.$$

Similarly, the residual energy of sensor $v$ is no less than the amount of energy $\frac{IE}{p*(1+\frac{1}{\gamma})}$, i.e. $IE - U(v) \geq \frac{IE}{p*(1+\frac{1}{\gamma})}$. Then, we have

$$1 - \theta(v) = 1 - \frac{U(v)}{IE} = \frac{IE-U(v)}{IE} \geq \frac{1}{p*(1+\frac{1}{\gamma})},$$

and

$$\theta'(v) = \frac{U'(v)}{IE} = \frac{IE*\theta(v)+\frac{IE}{p(1+\frac{1}{\gamma})}}{IE} = \theta(v) + \frac{1}{p(1+\frac{1}{\gamma})}.$$

**Target coverage algorithm.** For a given lifetime granularity $p$, how to construct connected sensor covers in the network to maximize the number $q$ of the connected sensor covers is critical to prolong the network lifetime, since the network lifetime is $\delta * q$. On one hand, it is expected that the total energy consumption in a sensor cover be minimized so that more sensor covers can be found. On the other hand, balancing the residual energy of sensors in the network by adding the sensors with high residual energy to a sensor cover can result in a larger $q$ as shown by the example in Fig. 1. Thus, we focus on finding a connected sensor cover with lifetime threshold $\delta$ such that the total energy consumption in the cover is minimized and the minimum residual energy among the sensors is maximized.

Let $\mathcal{C}$ be a sensor cover in construction at phase one. To minimize the energy consumption of the sensors in $\mathcal{C}$, we should include a sensor into $\mathcal{C}$ if it covers a larger number of uncovered targets by $\mathcal{C}$. On the other hand, to maximize the minimum residual energy of the sensors in $\mathcal{C}$, we should include a sensor that has more residual energy into $\mathcal{C}$. However, a sensor covering a larger number of uncovered targets may have small residual energy, while another sensor covering few uncovered targets may have substantial residual energy. It has been shown that a heuristic based on the exponential function of energy utility at nodes is very useful in the design of algorithms for unicasting and multicasting in ad hoc networks [14,15], which can balance the energy consumption among nodes. We here use an exponential function of energy utility at sensors and propose a heuristic function that tradeoffs residual energy and coverage ability of sensors. For a sensor $v \in V_S - \mathcal{C}$, we define $gain_{\mathcal{C}}(v)$ as the ratio of an exponential function of the energy utility at $v$ to the number of uncovered targets by $\mathcal{C}$ as follows. If $N_{\mathcal{C}}(v) \neq 0$, $gain_{\mathcal{C}}(v) = a^{\theta(v)}/N_{\mathcal{C}}(v)$, otherwise, $gain_{\mathcal{C}}(v) = \infty$, where $a > 1$, and $N_{\mathcal{C}}(v)$ is the number of uncovered targets by $\mathcal{C}$, i.e., $N_{\mathcal{C}}(v) = |\{t \mid t \in V_T, (v,t) \in E, \forall_{v' \in \mathcal{C}}\ (v',t) \notin E\}|$. It can be seen that a sensor $v$ with more residual energy and a larger number of uncovered targets has a smaller value of $gain_{\mathcal{C}}(v)$. Thus, a sensor with smallest value of $gain$ has the highest priority to be included in $\mathcal{C}$.

The construction of a sensor cover with lifetime threshold $\delta$ proceeds greedily. It maintains a subset $\mathcal{C}$ of $V_S$ and a set $T_{\mathcal{C}}$ that consists of the targets covered by $\mathcal{C}$. Initially, both $\mathcal{C}$ and $T_{\mathcal{C}}$ are empty sets. Each time a sensor $v$ is selected and added to $\mathcal{C}$ if it has the smallest value of $gain_{\mathcal{C}}(v)$ among the sensors that are not in $\mathcal{C}$ and sufficient residual energy for at least $\delta$ time units sensing and transmission, i.e., $1 - \theta(v) \geq 1/p$, following Lemma 1. The iteration continues until $\mathcal{C}$ is a sensor cover or no more sensors can be added to $\mathcal{C}$.

Having a sensor cover $\mathcal{C}$ with lifetime threshold $\delta$, we construct a Steiner tree with lifetime threshold $\delta$ rooted at the base station and spanning the sensors in $\mathcal{C}$. Since the residual energy among the sensors in the network is non-identical, the data transmission between a pair of neighboring sensors may be asymmetry. For example, sensor $u$ may have sufficient residual energy to transmit data to sensor $v$ but $v$ has no sufficient residual energy for transmitting data to $u$ for at least $\delta$ time units, given an edge $(u,v) \in E_S$. Thus, we introduce a directed, edge-weighted auxiliary graph $G'(V', E', w')$ based on the residual energy of the sensors in the network $G(V,E)$, which is constructed as follows. $V' = V$. For each $(u,v) \in E_S$, a directed edge $\langle u, v \rangle$ is added to $E'$ if $v$ has sufficient residual energy for at least $\delta$ time units sensing and/or transmission, that is, (i) $v \in \mathcal{C}$, since the lifetime of $\mathcal{C}$ is at least $\delta$ time units and thus each sensor in $\mathcal{C}$ has sufficient residual energy for at least $\delta$ time units sensing and transmission; or (ii) $v \notin \mathcal{C}$ and $1 - \theta(v) \geq 1/(p * (1 + \frac{1}{\gamma}))$, i.e., $v$ is not in $\mathcal{C}$ but has sufficient residual energy for at least $\delta$ time units transmission, following Lemma 1. Since the tree is rooted at the base station, the direction of data transmission is reverse to that of the directed edges in the tree. The weight $w'(u,v)$ assigned to edge $\langle u,v\rangle$ is an exponential function $b^{\theta(v)}$, where $b > 1$. After a directed, edge-weighted auxiliary graph $G'$ has been constructed, an approximate, minimum edge-weighted Steiner tree $\mathtt{T}'$ of $G'$ rooted at the base station and spanning the sensors in $\mathcal{C}$ is built. A tree $\mathtt{T}$ of $G$ used for data sensing and transmission is then derived from $\mathtt{T}'$ and the connected sensor cover is composed of the sensors in $\mathtt{T}$. The detailed algorithm, referred to as algorithm $\mathtt{TC}$, is as follows.

**Algorithm** `Target_Coverage` $(G, p)$
Input: sensor network $G$; lifetime granularity $p$; sensor lifetime $\tau$.
Output: network lifetime $lifetime$.
**begin**
1. $lifetime = 0$;
2. while $(true)$ do
3. $\mathcal{C} = \emptyset$; /* the sensor cover */
4. $T_{\mathcal{C}} = \emptyset$; /* the set of targets covered by $\mathcal{C}$ */
5. $flag = true$;
6. while $(flag \wedge (T_{\mathcal{C}} \neq V_T))$ do
7. find a sensor $v_0 \in V_S - \mathcal{C}$ such that
$$1 - \theta(v_0) \geq \frac{1}{p} \quad \text{and } gain_{\mathcal{C}}(v_0) = min\{gain_{\mathcal{C}}(v) \mid v \in V_S - \mathcal{C}\};$$
8. if $v_0$ exists then
9. $\mathcal{C} = \mathcal{C} \cup \{v_0\}$; /* $v_0$ is included in $\mathcal{C}$ */
10. $T_{\mathcal{C}} = T_{\mathcal{C}} \cup \{t \mid (v_0, t) \in E\}$;
/* add the uncovered targets by $\mathcal{C}$ into $T_{\mathcal{C}}$ */
else
11. $flag = false$;
endif;
endwhile;
12. if $(flag)$ then /* a sensor cover is found */
13. construct the auxiliary graph $G'(V', E', w')$;
14. find an approximate, minimum, edge-weighted Steiner tree $\mathtt{T}'$ of $G'$ rooted at the base station and spanning the sensors in $\mathcal{C}$;
15. if ($\mathtt{T}'$ *does not exist*) then
16. return $lifetime$;/* no further connected sensor covers can be found */
endif;
17. $V(\mathtt{T}) = V(\mathtt{T}')$;
18. $E(\mathtt{T}) = E(\mathtt{T}')$;
19. $lifetime = lifetime + \frac{\tau}{p}$;
20. if $v$ is a terminal node in tree $\mathtt{T}$ then
21. $\theta(v) = \theta(v) + \frac{1}{p}$;
else
22. $\theta(v) = \theta(v) + \frac{1}{p*(1+\frac{1}{\gamma})}$.
endif /* update the energy utility ratio at nodes */

```
    else
23.   return lifetime; /* no sensor covers can be found */
    endif
    endwhile
end
```

## 4 Performance Evaluation

We evaluate the performance of algorithm TC in terms of the network lifetime through experimental simulations. We first compare the network lifetime delivered by the algorithm for different lifetime granularities. We then evaluate the algorithm for various network connectivity among sensors. We finally analyze the impact of the connectivity between targets and sensors on the network lifetime.

**Simulation environment.** We assume that the monitored region is a $10m \times 10m$ square in which $n_s$ sensors and $n_t$ targets are deployed randomly by using the NS-2 simulator [16], where $n_s$ is set to be 100 and $n_t$ varies from 10 to 50 with increment of 10. We also assume that the transmission range $r_t$ of sensors is 3, 4, 5, 6 or 7. Each target in the sensor network is randomly connected to the sensors and has a node degree between $l_b * n_s$ and $u_b * n_s$, where $l_b$ varies from 0.1 to 0.25 with increment of 0.05 and $u_b$ is set to be 0.3. We further assume that sensor lifetime $\tau$ is 1000 time units and lifetime granularity $p$ is 1, 4 or 8. In addition, $\gamma$, $a$ and $b$ in the definition of function *gain* and $w'$ are set to be 2.

We generate 10 different topologies for $n_s$ sensors and 10 different topologies for $n_t$ targets randomly. For each of the 10 target topologies, each of the sensor topologies is applied to it and thus 100 different network topologies are generated for the given $n_s$ and $n_t$. The value of the network lifetime in all figures is the mean of the network lifetimes delivered by applying the proposed algorithm to 100 different network topologies.

**Performance evaluation of various algorithms.** We first evaluate the network lifetime delivered by the algorithm for different lifetime granularities when $r_t = 3$, $l_b = 0.1$ and $u_b = 0.3$. It can be seen from Fig. 2, that the algorithm with

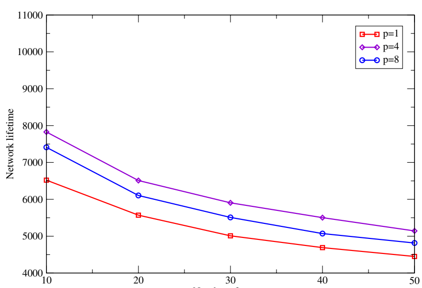
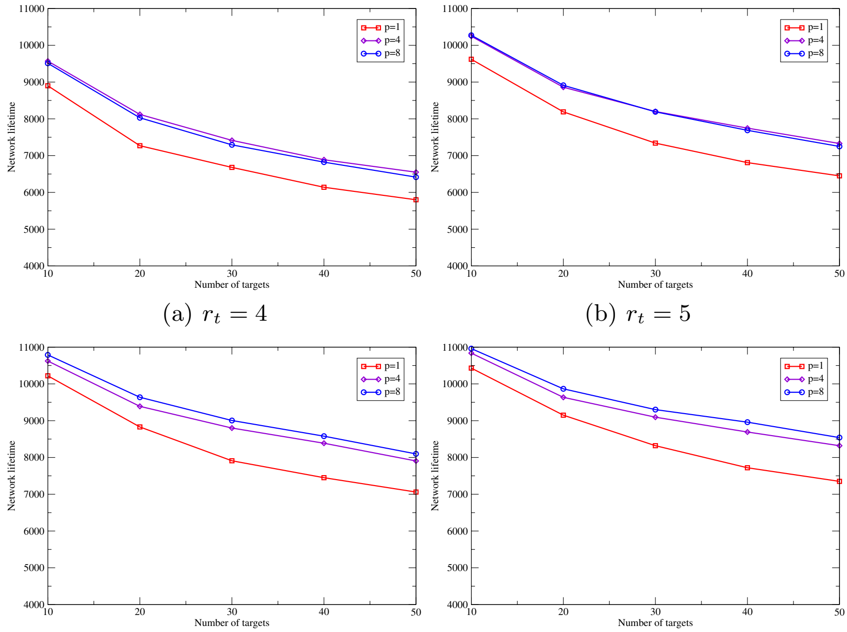



**Fig. 2.** Comparison of network lifetime delivered by algorithm TC for various lifetime granularities when $r_t$=3, $l_b = 0.1$ and $u_b = 0.3$




(a) $r_t = 4$ (b) $r_t = 5$

(c) $r_t = 6$ (d) $r_t = 7$

**Fig. 3.** Comparison of network lifetime delivered by algorithm TC for various lifetime granularities and transmission ranges when $l_b = 0.1$ and $u_b = 0.3$

lifetime granularity $p > 1$ outperforms the algorithm with $p = 1$. For example, the network lifetime delivered by the algorithm with $p = 4$ or $p = 8$ increases by around 20% or 14% when $n_t = 10$, compared the case where $p = 1$. The reason behind is that the sensor covers found when $p = 1$ are disjoint, whereas a sensor can be included in more than one sensor cover as long as they have sufficient residual energy for at least $\delta$ time units sensing and/or transmission when $p > 1$. It also can be seen from this figure that the network lifetime delivered by the algorithm with $p = 4$ is longer than that with $p = 8$, which implies that the network lifetime is not necessarily proportional to the value of $p$ for all network topologies. There are two factors that can cause the shorter network lifetime in algorithm TC. One is the sensor cover failure in Step 23 of the algorithm, where no further sensor covers can be found. The other is the connected sensor cover failure in Step 16 of the algorithm, where no further connected sensor covers exist. In our simulations, we found that more network disfunction is caused by the connected sensor cover failure when $p = 8$ than $p = 4$. For example, the percentage of network disfunction caused by the connected sensor cover failure is 76% when $p = 8$, whereas only 50% of the network disfunction is caused by the connected sensor failure when $p = 4$ for the case of $n_t = 10$. Thus, the network connectivity among the sensors is the bottleneck of the network lifetime for a finer lifetime granularity. We then evaluate the algorithm for various $p$ and

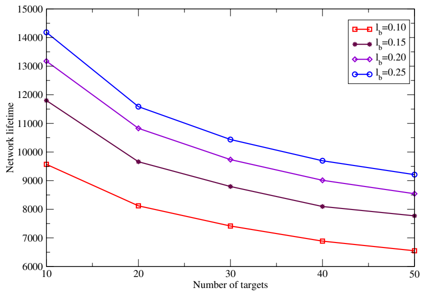



**Fig. 4.** Network lifetime delivered by algorithm TC for various connectivity between sensors and targets when $r_t = 4$, $p = 4$ and $u_b = 0.3$

network connectivity by increasing the transmission range $r_t$, i.e., improving the network connectivity among the sensors. As shown in Fig. 3, the performance of the algorithm is improved with the growth of the transmission range from 4 to 7 for various $p$. Particularly, the difference of the network lifetimes delivered by the algorithm with $p = 4$ and $p = 8$ drops with the growth of the transmission range, and the algorithm with $p = 8$ outperforms that with $p = 4$ for the case where the transmission range $r_t$ is 6 or 7 (Fig. 3(c) and (d)). This is due to the fact the percentage of network disfunction caused by the connected sensor cover failure drops, with the improvement of network connectivity among the sensors, and the network lifetime delivered by the algorithm with larger $p$ can be prolonged. In addition, similar to the case where $r_t = 3$ in Fig. 2, the network lifetime delivered by the algorithm with $p = 1$ is not as long as that with $p = 4$ or $p = 8$. We finally analyze the impact of the connectivity between sensors and targets on the network lifetime delivered by the algorithm when $r_t = 4$ and $p = 4$. We change $l_b$ from 0.1 to 0.25 with the increment of 0.05 while $u_b$ keeps 0.3. Fig. 4 shows that the network lifetime is prolonged further for the networks with improved network connectivity between sensors and targets, since the degree increase of each target results in the size decrease of each sensor cover and thereby more sensor covers can be found.

## 5 Conclusions

In this paper, we considered the target coverage problem in sensor networks by partitioning the sensor lifetime into $p$ equal intervals and allowing the overlapping among sensor covers. We first analyzed the energy consumption of sensors in a Steiner tree corresponding to a connected sensor cover. We then proposed a novel heuristic algorithm for the problem of concern that took into account both residual energy and coverage ability of sensors. We finally conducted experiments by simulation to evaluate the performance of the proposed algorithm for various lifetime granularities $p$ and network connectivity. The experimental results showed that the algorithm with $p > 1$ outperforms that with $p = 1$, and the network lifetime delivered by the proposed algorithm is further prolonged with the increase of lifetime granularity and improvement of network connectivity.

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