Power-Saving Scheduling for Multiple-Target Coverage in Wireless Sensor Networks

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Abstract—We address the multiple-target coverage problem (MTC) in wireless sensor networks (WSNs). We also propose an energy-efficient sensor-scheduling algorithm for multiple-target coverage (MTC) that considers both the transmitting energy for collected data and overlapped targets. We introduce two algorithms: one optimal, the other heuristic. Simulation results show that the proposed algorithms can contribute to extending the lifetime of network and that the heuristic algorithm is more practical than the optimal algorithm with respect to complexity.

Index Terms—Sensor scheduling, power saving, multiple targets, overlapped target.

I. INTRODUCTION

In WSNs, the sensor batteries have limited size and weight and, in most cases, are not rechargeable. Hence, the most interesting issue regarding WSNs is to extend the lifetime of the network. For this purpose, scheduling algorithms have been researched as a key technique. However, previous work on the topic has certain problems and limitations. In the past, it has commonly been assumed that sensors that have the same sensing range would gather the same amount of data and hence consume the same amount of energy when transmitting the collected data, regardless of how many targets they observed. However, different sensors will monitor different numbers of targets and a sensor that monitors more targets would gather more data [4]; hence it will consume more transmission energy. In addition, some targets are overlapped. These are redundant and result in energy being wasted by sensors.

In this letter, we propose a sensor-scheduling algorithm for MTC that considers the transmitting energy according to the number of targets covered by the sensor and removes the redundancy of overlapped targets. To evaluate the algorithm’s performance, we model the optimal sensor-scheduling algorithm as an integer programming that is proved to be NP-complete. To reduce the complexity of the optimal algorithm, we propose a heuristic algorithm.

II. SYSTEM MODEL

A. System Descriptions and Assumptions

We assume that the WSN consists of sensors, targets, and a sink node. The sensors transmit the collected data to a sink node using a routing protocol, such as LEACH [3]. Here, only one-hop transmission for the collected data is considered and the routing problem is not considered. The sensors are also aware of their own location by using GPS or some other localization mechanisms and the location of targets is fixed at a known position. As defined in [2], given that each target needs to be observed by the sensors continuously, we define the lifetime of the sensor network as the time that has elapsed until all the targets are covered by at least one sensor. We assume that a sensor covers a target if the distance between the sensor and the target is less than the sensing range.

For an example of four sensors (s) and four targets (k), a coverage relationship between sensors and targets is represented as follows: \( s_1 = \{k_1, k_2, k_3, k_4\}, \) \( s_2 = \{k_1, k_3\}, \) \( s_3 = \{k_1, k_2, k_4\}, \) \( s_4 = \{k_2, k_3\}. \) For \( s_2, \) the sensor \( s_2 \) covers target \( k_1 \) and \( k_3. \) Using the same method as presented in [2], we make the sensors form groups that consist of the minimum number of sensors based on the coverage relationship. Each sensor can be included in multiple groups, and each group completely covers all the targets. We define a group as a joint set. As illustrated in Fig. 1, we can make three joint sets for a given coverage relationship.

The sensor-scheduling mechanism operates in the manner presented in [2]. We design a sensor-scheduling algorithm by constructing the maximum number of joint sets for a given coverage relationship. Then, by determining the active time of each joint set, the lifetime of the network can be maximized while ensuring that all the targets are completely covered. Once the active time of the joint sets has been determined, each joint set is activated in order. Only the sensors in the activated joint set go into active mode for the purpose of observing all the targets and transmitting the sensed data to the sink node. Sensors in joint sets that have not been activated remain in sleep mode, to conserve power.

B. Multiple-target Coverage Problem

We consider a periodic sensing application in which the sensor attempts to detect targets periodically. The more targets a sensor monitors, the more data it will collect. The energy

Fig. 1. Overlapped target and corresponding overlapping sensors in joint sets.
used to transmit the collected data will be in proportion to the number of targets that the sensor covers.

We derive the energy consumption of a sensor in MTC as follows. For a given active time of sensor $t_{active}$, the energy consumption of sensor $E_{sensor}(t_{active})$ is expressed as the sum of the sensing and transmission energy. As addressed in [1], the sensor consumes negligible sensing power to transmit the collected data during $P_{tx}$.

$$E_{sensor}(t_{active}) \approx P_{tx} \times t_{tx} \text{ where } P_{s} \ll P_{tx} \quad (1)$$
$$= P_{tx} \times (t_{active} \times \alpha N_t)$$

Here, $t_{tx}$ is the transmission time of the sensor, and the transmission energy $P_{tx} \times t_{tx}$ is decided according to the number of targets covered by the sensor $N_t$ and the duration of time that it spends for sensing. Given that the sensor gathers data all the time during $t_{active}$, the sensing time is equal to $t_{active}$. Therefore, $P_{tx} \times t_{tx}$ can be expressed by $P_{tx} \times t_{active} \times \alpha N_t$, which means the amount of energy that is consumed to transmit the collected data during $t_{active}$.

As $\alpha$ increases, the aggregate rate of a sensor is decreased. That is, for the same $t_{active}$ and $N_t$, the amount of data that the sensor transmits to a sink node increases; hence, the sensor uses more energy. We assume that all the sensors have the same initial energy. Each sensor can be active for a unit time of 1 when it covers only one target. That is, the initial energy consumption of a sensor is equal to $E_{sensor}(t_{active}) = P_{tx}$ when $t_{active} = 1$, $N_t = 1$, and $\alpha = 1$. We normalize this initial energy as 1.

III. PROPOSED SENSOR-SCHEDULING ALGORITHM

A. Optimal Algorithm

We assume that there are $N$ sensors to monitor $M$ targets in the WSN. We define $S = \{s_1, s_2, \ldots, s_N\}$ as the set of $N$ sensors, and $T = \{k_1, k_2, \ldots, k_M\}$ is the set of $M$ targets. $J_1, J_2, \ldots, J_P$ are the joint sets, where $P$ is the maximum number of joint sets for a given coverage relationship between $S$ and $T$. We also define the following relationships and variables.

- $C_m = \{i |$ sensor $s_i$ covers target $k_m\}$: the indices of a sensor that covers target $k_m$ where $m = 1, \ldots, M$
- $B_l = \{i |$ sensor $s_i$ covers target $l\}$: the indices of a sensor that covers target $l$ where $l = 0, \ldots, M$
- $x_{ij}$: Boolean variable; if sensor $s_i$ is a member of the joint set $J_j$, $x_{ij} = 1$; otherwise, it is 0.
- $y_i$: integer variable between $[0, M]$; $y_i$ is if and only if sensor $s_i$ is a member of $B_l$ where $l = 1, \ldots, N$
- $t_{ij}$: real variable $0 \leq t_{ij} \leq 1$; $t_{ij}$ is the allocated active time for the joint set $J_j$ where $j = 1, \ldots, P$

In the MTCP, there exists an overlapped target (OT) that is sensed by adjacent sensors at the same time. We call these adjacent sensors that monitor the same target at the same time overlapping sensors (OSs) for the corresponding OT. The OSs gather the overlapped data and transmit them to a sink node. Obviously, multiple transmissions of the same data is redundant and causes the sensors to waste energy. To eliminate the redundancy of OTs, we propose an energy-efficient method in which only one responsible sensor (RS) among the OSs transmits the overlapped data to the sink node, while the other OSs do not transmit. To select the correct RS among the OSs, we define the following relationships and variables.

- $C_{m_j} = \{i |$ sensor $s_i$ is responsible for target $k_m$ when $J_j$ is active $\}$ where $m = 1, \ldots, M$ and $j = 1, \ldots, P$
- $D_{ij} = \{i |$ sensor $s_i$ is responsible for target $l$ number of targets when $J_j$ is active $\}$ where $l = 0, \ldots, M$ and $j = 1, \ldots, P$
- $W_{ij}$: integer variable between $[0, M]$; $W_{ij}$ is if and only if sensor $s_i$ is a member of $D_{ij}$

Given that only sensors in the same joint set are active at the same time, we find the OTs and corresponding OSs for each joint set as shown in Fig. 1. Therefore, we propose a responsible sensor selecting algorithm (RSSA) for a joint set $J_j$. Obviously, a critical target, which is covered by the minimum number of sensors, is the bottleneck in view of the lifetime of the network. To maximize the network’s lifetime, an OS that does not cover the critical target and monitors a smaller number of targets is selected as an RS, $s_r$. Once $s_r$ is selected from the OSs, the number of targets covered by each OS except $s_r$ is reduced by 1 because only $s_r$ transmits the data of the OT.

Algorithm 1: RSSA for a joint set $J_j$

01: % Initiate for $m = 1, \ldots, M$, $l = 0, \ldots, M$, and $i = 1, \ldots, N$
02: Set $C_{m_j} = C_m$, $D_{ij} = B_i$, and $W_{ij} = y_i$
03: Find overlapped targets in $J_j$: OT $J_j$
04: for all targets $k_m \in OT J_j$
05: Find overlapping sensors that cover $k_m$: OS $k_m J_j$
06: Select a responsible sensor $s_r \in OS k_m J_j$
07: % Update for selected responsible sensor
08: for all sensors $s_i \in OS_k_m J_j$ and $s_i \neq s_r$
09: $C_{m_j} = C_{m_j} - 1$
10: $D_{ij} = D_{ij} - i$, and $D_{(l-1)i} = D_{(l-1)i} + i$
11: $W_{ij} = W_{ij} - 1$
12: end for
13: end for
14: Return updated $C_{m_j}$, $D_{ij}$, and $W_{ij}$

In the optimal algorithm, to select the RSs and update $C_{m_j}$, $D_{ij}$, and $W_{ij}$ for $J_1, J_2, \ldots, J_P$, the RSSA for $J_j$ is executed $P$ times where $j = 1, 2, \ldots, P$. Finally, we derive the optimal algorithm, which is described as an Integer Programming problem, as follows.

Maximize $\sum_{j=1}^{P} t_j$

subject to $\sum_{i=1}^{C_m} (\alpha W_{ij} x_{ij} t_j) \leq 1$ for all $s_i \in S$
$\sum_{i=1}^{C_m} x_{ij} \geq 1$ for all $k_m \in T$, $j = 1, \ldots, P$

where $x_{ij} = 0, 1$ ($x_{ij} = 1$ if and only if $s_i \in J_j$)
$W_{ij} = 1$ if and only if $s_i \in D_{ij}$

The objective function is set to maximize the network’s lifetime, which is the sum of the assigned active times for all the joint sets. The first constraint indicates the limited energy of sensors. By allocating the active time $t_j$ to the joint set $J_j$, the sensors in the joint set $J_j$ consume the energy according to $\alpha W_{ij} t_j$. For all $s_i \in S$, if a sensor $s_i$ belongs to more than one joint set, given the sum of the active times of the joint sets that
contain the sensor $s_j$, it is guaranteed that the total consumed energy of sensor $s_j$ does not exceed the initial energy of the sensor, 1. The second constraint guarantees that all the targets $k_m \in T$ must be covered by at least one sensor in each joint set $J_j$ for $j = 1, \ldots, P$. In [2], the authors demonstrated that this kind of maximization problem is NP-complete.

B. Heuristic Algorithm

We now propose a heuristic algorithm in order to compute the joint sets efficiently which operates as follows.

Algorithm 2: Heuristic Algorithm

01: % Initialization
02: Set initial lifetime of sensors, $S_S = S$, $j = 0$
03: while each target is covered by at least one sensor in $S_S$
04: % Make a new joint set $J_j$
05: $j = j + 1$, $J_j = \emptyset$, $S_T = T$
06: while $S_T \neq \emptyset$
07: Find a critical target $k_{\text{critical}} \in S_T$
08: Select a sensor $s_{\text{select}} \in S_S$
09: $J_j = J_j \cup s_{\text{select}}$
10: for all targets $k_m \in S_T$
11: if target $k_m$ is covered by $s_{\text{select}}$
12: $S_T = S_T - k_m$
13: end while
14: % Select responsible sensors for a joint set $J_j$
15: Execute the RSSA
16: % Lifetime update
17: for all sensors $s_i \in J_j$
18: $\text{lifetime}_{s_i} = \text{lifetime}_{s_i} - \alpha w W_{ij}$
19: if $\text{lifetime}_{s_i} - \alpha w W_{ij} \leq 0$
20: $S_S = S_S - s_i$
21: end for
22: end while
23: Return joint sets $J_1, \ldots, J_j$ and the network’s lifetime $j \times w$

First, the heuristic algorithm initiates the energy of the sensors, the iteration number $j$, and the set of sensors $S_S$. Second, the heuristic algorithm iteratively makes a joint set. The set of targets $S_T$ contains the targets that should be covered by the current joint set $J_j$. The sensor that covers the critical target while it covers a larger number of uncovered targets in $S_T$ is selected as $s_{\text{select}}$ from $S_S$. Then, $s_{\text{select}}$ is contained in $J_j$, and the targets covered by $s_{\text{select}}$ are removed from $S_T$. When all the targets are covered by $J_j$, a new joint set is formed. Third, after a joint set $J_j$ has been formed, the heuristic algorithm executes the RSSA to select the RS and obtain the updated $C_{mj}$, $D_{ij}$, and $W_{ij}$ for $J_j$. Fourth, the heuristic algorithm schedules $J_j$ for $w$ and updates the lifetime of the sensors in $J_j$, $w \in [0, 1]$ is an active time unit for a joint set. Given that $J_j$ is active for $w$, the sensors in $J_j$ consume energy, $\alpha w W_{ij}$. The $S_S$ maintains the sensors that have sufficient energy to be members of additional joint sets. Once a sensor’s energy is insufficient, the sensor is removed from the set of available sensors $S_S$. The second, third, and fourth procedures of the heuristic algorithm are followed repeatedly until each target is covered by at least one sensor in the set $S_S$. Finally, the heuristic algorithm returns the total joint sets $J_1, \ldots, J_j$ and the network’s lifetime $j \times w$. The complexity of the proposed heuristic algorithm is expressed as $O(jM^2N)$, while the complexity of the optimal algorithm is NP-complete.

IV. SIMULATION RESULTS AND CONCLUSIONS

We evaluated and analyzed the performance of the proposed algorithms for a relatively small number of sensors and targets. Our simulation environment considered a fixed network with $N$ sensors and $M$ targets deployed randomly in a 500$m \times 500$m area. We assumed that all sensors have a sensing range of 250$m$. In the simulation, we varied the number of sensors $N$ from 20 to 50. We fixed the number of targets $M$ to 10 and the transmission load factor $\alpha$ to 0.5.

Fig. 2 shows the network lifetime of the optimal and heuristic algorithms compared with a conventional scheme. The conventional scheme shows the maximum lifetime of network when the redundancy of OTs is not eliminated. Thus, the network lifetime is increased by 70% when the optimal algorithm is used, and by 40% when the heuristic algorithm is used. This implies that the proposed algorithms can contribute to extend the network lifetime.

As the number of sensors increases, the performance gain of the proposed algorithms increases. When more sensors are deployed, each target is covered by a greater number of sensors and hence a greater number of joint sets can be formed. Therefore, the total number of OTs in all the joint sets is also increased. That is, the performance gain that results from eliminating the redundancy of OTs increases. Also, the optimal algorithm performs better than the heuristic algorithm, but the complexity of optimal algorithm renders it impractical to use in real-world applications, while the complexity of the heuristic algorithm is small enough to perform efficiently in real time.

REFERENCES