Energy-Efficient Connected Coverage of Discrete Targets in Wireless Sensor Networks[⋆]

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Abstract. A major concern in wireless sensor networks is to maximize network lifetime (in terms of rounds) while maintaining a high quality of service (QoS) at each round, which includes target coverage and network connectivity. Due to the power scarcity of sensors, a mechanism that can efficiently utilize energy has a great impact on extending network lifetime. Most existing works concentrate on scheduling sensors between sleep and active modes to maximize network lifetime while maintaining target/area coverage and network connectivity. This paper generalizes the sleep/active mode by adjusting sensing range to maximize the total number of rounds. Two distributed solutions have been proposed and simulation results confirm the efficiency of our solutions.

Keywords: wireless sensor networks, energy efficiency, target coverage, sensor connectivity, network lifetime

1 Introduction

The paramount concern in wireless sensor networks (WSNs) is power scarcity, driven partially by battery size and weight limitations. Mechanisms that optimize sensor energy utilization have a great impact on extending network lifetime. Power saving techniques can generally be classified into two categories: scheduling sensors to alternate between active and sleep mode, or adjusting their sensing ranges. In this paper, we combine both methods by dynamic management of node duty cycles in a high target density environment. In this approach, any sensor adjusts its sensing ranges from 0 to its maximum range, where range 0 corresponds to sleep mode.

Target coverage characterizes the monitoring quality of WSNs. The general requirement of target coverage is that each target should be covered by at least one sensor. The energy consumption of target coverage is the total energy consumed by all sensors. The problem with a single sensing range is that there are a lot of targets covered by several active sensors, which causes redundancy in energy consumption. Adjustable sensing

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However, target coverage is not the only responsibility of WSNs. To reduce network overhead and energy consumption, WSNs should also provide satisfactory network connectivity so that sensors can communicate for data gathering or data fusion.

In this paper, we study the problem of maximizing network lifetime (in terms of rounds) in WSNs, where in each round sensor-target coverage and sensor connectivity are maintained. Unlike the traditional approaches [12], [14] in area coverage where the connectivity is trivialized by assuming that the transmission range is at least twice that of the sensing range, we focus on a more generic connectivity condition that can be used even when the transmission range is less than twice the sensing range. Instead of just identifying connected active sensors for one round, we focus on extending the network lifetime. Thus, we assume both sensing targets and transmitting data consume energy. Since data is gathered less frequently than target sensing, we adopt a transmission usage ratio to characterize the frequency of data transmission within the network lifetime.

Although maximizing the lifetime of WSNs by scheduling sensors' activity is not a new problem, none of the existing algorithms deal with the case of scheduling sensors' activity by self-configuring sensing ranges in the environment where both discrete target coverage and network connectivity are satisfied.

The main contributions of this paper are: 1) introducing the adjustable sensing range connected sensor cover (ASR-CSC) problem, where target coverage and connectivity are maintained, 2) presenting a generic connectivity condition, 3) designing efficient distributed heuristics to solve the ASR-CSC problem, 4) demonstrating the performance of our approaches through simulations.

The rest of the paper is organized as follows. In section 2 we present related works on coverage and connectivity problems. Section 3 formulates the ASR-CSC problem and section 4 presents our heuristic contributions. In section 5 we present the simulation results and section 6 concludes our paper.

2 Related Work

The general target coverage problem is introduced in [1], where the problem is modelled as finding a maximal number of disjoint set covers, such that every cover completely monitors all targets. The general problem is NP-complete [1]. This problem is extended further in [2], where sensors are not restricted to participation in only disjoint sets, i.e. a sensor can be active in more than one set.

Authors in [15] study area coverage and connectivity in an unreliable wireless sensor grid network, and present a necessary and sufficient condition for coverage and connectivity. In [14], a sufficient condition is given: the transmission range being larger than twice the sensing range, under which coverage implies connectivity. A similar sufficient condition is considered in [12] in the environment that requires target coverage and connectivity of active sensors in a large scale WSN. Although the connectivity can be relatively easy to specify in the environment with area coverage and uniform sensing range, such a condition will be hard to specify in the environment with adjustable sensing range and discrete target coverage. In this paper, we present a generic way to address this problem.

The work most relevant to our approach is [3], which extends [2] with adjustable sensing range in point coverage (where targets are discrete). Compared with [3], we are also concerned with maintaining network connectivity for the ASR-CSC problem. We analyze the impact of connectivity on energy efficient management sensors, and design distributed heuristics to maximize the lifetime of WSNs.

3 Problem Formulation

We have two important assumptions in this paper: 1) All sensors in WSNs are connected; otherwise, no connected sensor set can be built. 2) Any target should be located in the maximal sensing range of at least one sensor; otherwise, target coverage cannot be guaranteed. In this paper, we compute the sensor-target coverage and sensor-sensor connection relationship based on Euclidean distance, i.e., a sensor covers a target with sensing range r_k if the Euclidean distance between them is no greater than r_k, and sensor i is connected to sensor j if their Euclidean distance is no greater than transmission range d_c. In this paper, we adopt a fixed transmission range d_c and adjustable sensing ranges $R = \{r_0, r_1, \cdots, r_k, \cdots, r_P\}$, in which r_k is the kth sensing range. In particular, $r_0 = 0$ is zeroth sensing range, corresponding to sleep mode, r_1, the minimum sensing range in active mode, is the 1st sensing range, and r_P, the maximum sensing range, is the Pth sensing range. For convenience, we index sensor i's selected sensing range by $p(i)$, and $p(i) = k$ means sensor i's current sensing range is the kth range r_k. For consistency, we use R_c to denote the transmission range set, i.e., $R_c = \{d_c\}$. We denote S, T to be the set of sensors and the set of targets respectively, in which $s_i \in S$ means sensor i, and $t_j \in T$ represents target j. Finally, we define $S(i)$, the sensors within s_i's transmission range.

Upon above notations, we model our problem on graph $G_U \cup G_D$, where $G_U = (S, R_c, E_S)$ is the sensor communication graph, and $G_D = (S \cup T, R, E_D)$ is the sensor-target coverage graph. G_U is undirected because sensors' communication ranges are the same, and G_D is directed because different sensors can set different sensing ranges. $E_S = \{(s_i, s_j) | \ |s_i s_j| \leq d_c\}$ is a subset of $S \times S$, which characterizes the direct connection between any two sensors. $E_D = \{(s_i, r_{p(i)}, t_j) | \ |s_i t_j| \leq r_{p(i)}\}$ is a subset of $S \times R \times T$, which represents the sensor-target coverage relationship. Triple $(s_i, r_{p(i)}, t_j)$ means sensor s_i with sensing range $r_{p(i)}$ covering target t_j. Let $S_a = \{s_i | p(i) > 0, \forall s_i \in S\}$ be the set of active sensors in each round. **Target coverage** is defined as: at any given time during the lifetime of a WSN, $\forall t_j \in T$, $\exists s_i \in S_a$ such that $(s_i, r_{p(i)}, t_j) \in E_D$. A WSN's connectivity depends on the connectivity of its communication graph G_U, so we can adopt the following definition, **network connectivity**: $\forall s_i, s_j \in S_a$, $\exists s_{i_1}, s_{i_2}, \cdots, s_{i_m} \in S_a$, such that (s_i, s_{i_1}), (s_{i_1}, s_{i_2}), $\cdots$, $(s_{i_m}, s_j) \in E_S$. Thus, our problem can be formally defined as follows:

Definition 1. (ASR-CSC Problem) *Given a set of targets and a set of sensors with adjustable sensing ranges in a WSN, schedule sensors' sensing ranges such that the WSN's lifetime is maximized, under the conditions that both target coverage and net-*

work connectivity are satisfied, and each sensor's energy consumption should be no more than initial energy E.

As mentioned in the introduction, we need to formalize the energy consumption so that we can identify energy consumption for different sensing ranges as well as the energy consumption of data transmission. Both types of energy consumption are proportional to their corresponding ranges. That is, sensing energy is proportional to sensing range and transmission energy is proportional to transmission range. However, energy consumption can be either biquadratic, quadratic, or linear to its corresponding range. In this paper, we consider quadratic and linear for sensing energy consumption, and biquadratic and quadratic for transmission energy consumption.

Target sensing is executed in each round, but data transmission is not executed so often. In this paper, we adopt transmission usage ratio, β, to characterize the frequency of data transmission within the network lifetime. In general, if the transmission usage ratio is β then transmission occurs once for every $\frac{1}{\beta}$ rounds. For example, $\beta = 0.01$ represents active sensors will in average transmit sensing data once every 100 rounds.

We denote

$$e_k = f(r_k) = \begin{cases} c_s \cdot r_k, & \text{linear model} \\ c_s \cdot r_k^2, & \text{quadratic model} \end{cases}$$

to be sensing energy consumption, where c_s is the sensing constant and r_k is kth sensing range. In the same way, we define the transmission energy consumption

$$g_e = f(d_c) = \begin{cases} \beta \cdot c_t \cdot d_c^2, & \text{quadratic model} \\ \beta \cdot c_t \cdot d_c^4, & \text{biquadratic model} \end{cases}$$

where β is the transmission usage ratio, c_t is transmission constant, and d_c is the transmission range. According to [17], the ratio $c_s : c_t$ can range from 19 to 35. A comparison of these parameters will be illustrated in section 5.

Since the AR-SC problem [3] is a special case of the ASR-CSC problem, formed by assuming the communication graph G_U to be a complete graph, according to restriction method [6], the ASR-CSC problem is NP-complete.

Figure 1 shows an example with four sensors s_1, s_2, s_3, s_4 and four targets t_1, t_2, t_3, t_4. In this example we assume a sensor's sensing area is a disk centered at the sensor, with a radius equal to the sensing range. Each sensor has two sensing ranges r_1, r_2 with $r_1 < r_2$. We use circles with solid lines to denote sensing areas with range r_1, circles with dotted lines for areas with range r_2, and heavy solid lines for transmissions within range d_c. The sensor-target coverage relationships are illustrated in Figure 1 (a) and Figure 1 (c). Figure 1 (c) shows the targets covered by each sensor with range r_1 : $(s_1, r_1) = \{t_1\}$, $(s_2, r_1) = \{t_2\}$, $(s_3, r_1) = \{t_3\}$, and $(s_4, r_1) = \{t_4\}$. Figure 1 (a) shows the targets covered by each sensor with range r_2: $(s_1, r_2) = \{t_1, t_3\}$, $(s_2, r_2) = \{t_2, t_4\}$, $(s_3, r_2) = \{t_3\}$, and $(s_4, r_2) = \{t_4\}$. The sensors' connection relationships are presented in solid lines, i.e., $S(s_1) = \{s_3, s_4\}$, $S(s_2) = \{s_3, s_4\}$, $S(s_3) = \{s_1, s_2, s_4\}$, $S(s_4) = \{s_1, s_2, s_3\}$.

All possible connected sensor covers C_1, C_2, C_3 are illustrated in Figure 1 (c), (d), and (e) respectively, where $C_1 = \{(s_1, r_1)$, (s_2, r_1), (s_3, r_1), $(s_4, r_1)\}$, $C_2 = \{(s_1, r_1)$, (s_2, r_2), $(s_3, r_1)\}$, and $C_3 = \{(s_1, r_2)$, (s_2, r_1), $(s_4, r_1)\}$. Figure 1 (b) shows a sensor

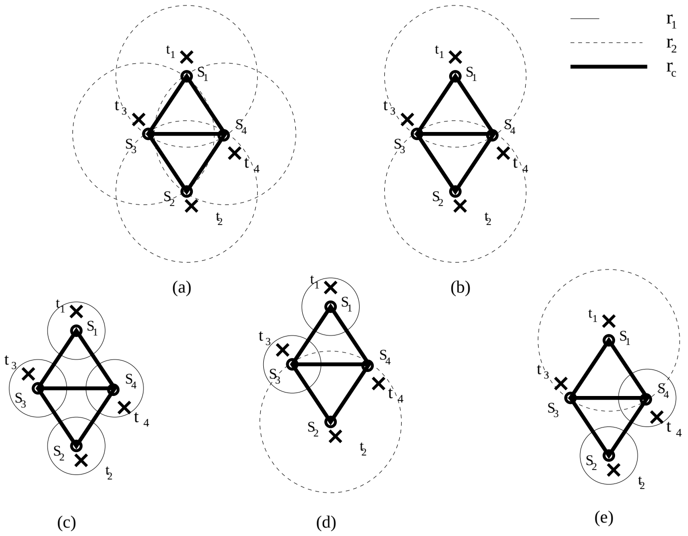

Fig. 1. Example of connected sensor covers

cover which does not meet the connectivity requirement because s_1 and s_2 are not within each other's communication range.

In this example, we assume $E = 2.4$, $e_1 = 0.5$, $e_2 = 1$, and $g_e = 0.1$. Each set cover is active for a unit time of 1. The optimal solution has the following sequence of sensor covers: C_1, C_1, C_1, C_1 with maximum lifetime 4. After that, all sensors run out of energy.

If sensors do not have adjustable sensing ranges and the sensing range is equal to r_2, then all sensors should be active. The reason is that s_1 and s_2 have to be active to cover t_1 and t_2, and one of s_3 and s_4 has to be active to maintain connectivity. Sensors can be organized in two distinct set covers, i.e., $C_4 = \{s_1, s_2, s_3\}$ and $C_5 = \{s_1, s_2, s_4\}$. But no matter how we schedule the set of sensors, the life time can be no more than 2. Therefore, this example shows a 100% lifetime increase when adopting adjustable sensing ranges.

4 Solutions for the ASR-CSC Problem

In this section, we present two different localized heuristic algorithms. The two algorithms differ in the order of the satisfaction of coverage and connectivity requirements. In the first algorithm, we first satisfy the connectivity requirement and then ensure target coverage. In this second algorithm, we reverse the order of satisfaction of connectivity and target coverage requirements.

In traditional area coverage, connectivity is automatically satisfied if $d_c \geq 2 \cdot r_k$ for the case of uniform sensing range r_k. However, this result does not apply to point coverage even when $r_k = r_P$. A simple illustration is shown in Figure 2, where heavy

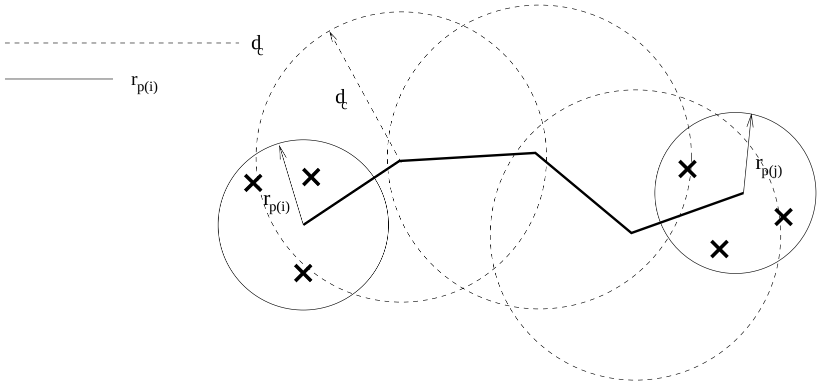

Fig. 2. Sensors contribute only for connectivity

solid lines represent a connected path, circles with light dotted lines denote transmission areas, and circles with light solid lines denote sensing areas. Two sensors i and j with sensing ranges $r_{p(i)}$ and $r_{p(j)}$ respectively take the responsibility of covering discrete targets. However, i and j are so far apart that even a range d_c ($\geq 2 \cdot r_{max}$) cannot directly connect i and j. Therefore, we have to select some sensors not only for target coverage but for connecting i and j. In this case, three other sensors have to be active just for connectivity.

Besides the case of a relatively large transmission range, we also need to be careful about the case of the transmission range being far less than the maximal sensing range. As illustrated in Figure 3, in which light dotted lines represent connectivity relationships while the circle with a solid line represents the sensing coverage area, because of the small transmission range a sensor has to collect the target information of all the sensors within its maximal sensing range. Any sensor within its maximal sensing range can cover targets within its transmission range. The problem is that the sensors within a sensor's maximal sensing range can be more than one hop neighbors so that the targets' information needs to be broadcast through multi-hop. The broadcast issue is beyond the scope of this paper. We will abbreviate the details.

Instead of narrowing our efforts to the relationship between target coverage and network connectivity, we focus on finding generic ways to satisfy both discrete target coverage and network connectivity. In the first algorithm, we build a virtual backbone first to satisfy network connectivity, and then ensure coverage.

4.1 Virtual Backbone Based Algorithm

We first give a high level view of the first algorithm, which works in rounds. Each round consists of an initialization phase and a working phase. In the initialization phase, the following steps execute: 1) Construct a virtual backbone for the WSN. 2) For each sensor in the virtual backbone, set its transmission range d_c and calculate its transmission energy consumption. 3) All sensors including inactive sensors (dominatees) together

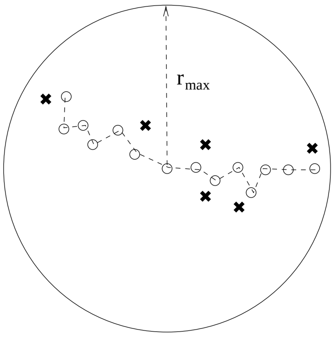

Fig. 3. Transmission range far less than the maximal sensing range r_{max}

with active sensors in the virtual backbone (dominators) iteratively adjust their sensing ranges based on contribution (the ratio of the number of covered targets to $e_{p(i)}$, corresponding to $r_{p(i)}$) until a full coverage is found. 4) Each sensor i active for sensing loses $e_{p(i)} + g_e$ from its residual energy, while sensors active only for connectivity each lose g_e.

After the initialization phase, each sensor works or sleeps in the following working phase according the schedule in the initialization phase. We assume that sensors initialize their clocks at the beginning and their clocks are accurate. The length of the initialization phase is fixed and so is the working phase, therefore, the length of a round is constant. Because the length of a round is constant, sensors have priori knowledge about when each round begins. Active sensors in previous round will continue working in the initialization phase to maintain connectivity and coverage.

Note that all sensors within the virtual backbone will consume energy for transmission, while sensors active for sensing will consume sensing energy besides transmission energy. This is because sensing sensors need to transmit the collected sensing data.

To provide such a virtual backbone in our algorithm, we first construct a connected dominating set and prune redundant sensors by applying Rule-k in [13]. Since it is a distributed and localized method, to ensure network connectivity, we have to assume that the sensors in a given area are dense enough so that all sensors in that area are connected.

In this method, each sensor determines its status (active/sleep) by applying an eligibility rule. If it meets the rule's requirement, then it decides to sleep; otherwise, it chooses to work for the rest of the round. We formally define the rule : let $S_h(i)$ be the sensors in $S(i)$ (Note $S(i)$ is i's neighbor sensors) with higher priority , which can be node ID or remaining energy, than i's. i is able to sleep if and only if the following conditions are satisfied: 1) Sensors in $S_h(i)$ are connected. 2) Sensor i's low priority neighbors $S(i) - S_h(i)$ are covered by sensors in $S_h(i)$.

The result of this connectivity initialization phase is the set of connected active sensors (dominators). We present the connectivity initialization phase. This phase is run by each individual sensor before the coverage initialization phase.

Connectivity Initialization

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start a timer $t_i \leftarrow \frac{W}{b(i)}$
if receiving notification message from $s_j$ before $t_i$ expires then
    $S_h(i) \leftarrow S_h(i) \cup j$;
    Construct subgraph $(S(i), E_{S(i)})$;
    if $S_h(i)$ is connected and covers $S(i) - S_h(i)$ then
        set transmission range 0;
if Timeout then
    Send notification message to neighbors;
```

In the above algorithm, $b(i)$ denotes the residual energy of sensor i, $S_h(i)$ is i's high priority neighbor set, which have higher residual energy than that of i or have higher ID when residual energies are equal, and W is the predetermined longest back-off time. Higher residual energy sensors are assigned higher priorities to balance energy consumption among sensors in the virtual backbone.

In forming the virtual backbone, each sensor i determines its responsibility by testing Rule-k. If it is satisfied, i decides to sleep; otherwise, it chooses to work. After the connectivity initialization phase, all dominators will be active for the rest of the round. A second phase is issued to guarantee target coverage. In the second phase, dominatees combined with dominators will jointly take the responsibility to ensure target coverage, and a sensor's sensing range is increased based on its contribution to target coverage. Once the second phase is done, the sensors with positive sensing range together with sensors in the virtual backbone will form the connected sensor cover, while all other sensors will be off-duty in the current round.

To complete our algorithm, we informally describe the coverage initialization phase. For the coverage initialization phase, we use a distributed algorithm similar to the one in [3] to handle target coverage. For brevity, we just describe the main idea of the target coverage algorithm.

In each round, each sensor i backs off a time in reverse proportion to its maximal contribution. If, before the back-off time is up, it receives messages from its neighbors, it reduces its uncovered target set, recalculates its contribution, and adjusts its back-off time. When the back-off time is up, it broadcasts $p(i)$ (that corresponds to the maximal contribution) and its covered target set to its neighbors. At the end of this stage, all the targets will be covered.

4.2 Coverage Based Algorithm

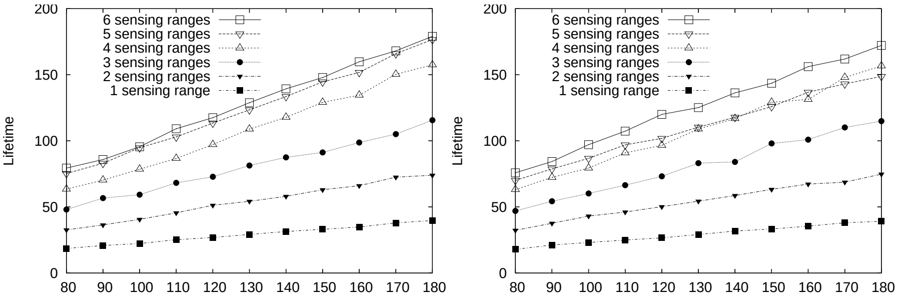
In this section, we present another algorithm which satisfies target coverage first. In this second algorithm, we first apply a greedy method to build target coverage and then apply Rule-k to connect the active sensors. The coverage initialization is the same as that of the first algorithm. There are a few differences in the connectivity phase of the two algorithms. In the second algorithm, after coverage initialization, the active sensors for sensing will be set to the highest priority for selection of the virtual backbone because sensing sensor also need to transmit data. The other sensors will set priority based on their residual energy. The sensors with higher priority will be selected first.

Since the coverage and connectivity phases are similar to those in the virtual backbone based algorithm, we present only a high level view of the coverage based algorithm. Similarly, the coverage based algorithm also works in rounds. At the beginning of each round the following steps execute: 1) All sensors iteratively adjust their sensing ranges based on their contributions. Each time a sensor with maximal contribution is selected and a corresponding sensing range is set. This process repeats until all of the targets are covered. 2) The active sensors within coverage are given the highest priorities, and Rule-k is applied to ensure network connectivity. 3) Each active sensor i subtracts $e_{p(i)} + g_e$ from its residual energy.

5 Simulation Results

In this section, we give an evaluation of our distributed algorithm. Our simulations are based on a stationary network with sensor nodes and targets randomly located in a $130m \times 130m$ area. We assume sensors are homogeneous and initially have the same energy. In the simulation, we consider the following tunable parameters: 1) the number of sensor nodes N, 2) the number of targets M, 3) the number of positive sensing ranges P, 4) unit time slot d, 5) transmission usage ratio β. Note that d defines the minimal time slot in which sensor can distinguish any two events. Different time slots help illustrate the impact of the transfer delay on the performance of the distributed greedy heuristics. Besides the tunable parameters, we set $c_s : c_t$ ratio to 19.

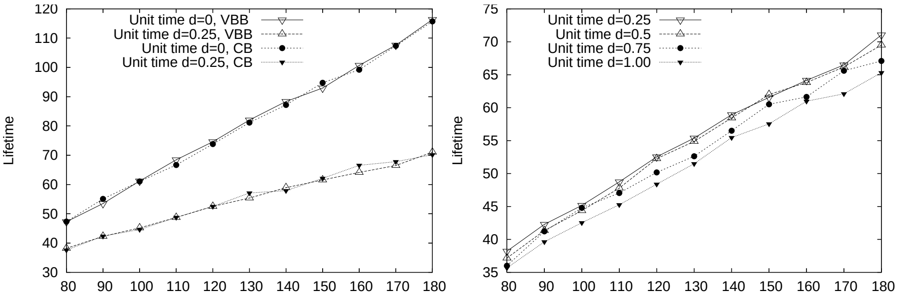
Since we are concerned with the benefit of adjustable sensing ranges on extending network lifetime, we consider the adjustable sensing range first. We observe the network lifetime when sensors support up to 6 sensing range adjustments. We compare 6 different schemes: fixed sensing range, 2 adjustable sensing ranges, 3 adjustable sensing ranges, 4 adjustable sensing ranges, 5 adjustable sensing ranges, and 6 adjustable sensing ranges. We set the same maximal sensing range ($60m$) for each scheme and in a scheme with $i(i = 1, 2, 3, 4, 5, 6)$ sensing ranges we set the sensing ranges to be $\frac{1\times 60}{i}m$, $\frac{2\times 60}{i}m, \cdots$, $\frac{i\times 60}{i}m$,. For example, for $i = 6$, the 6 sensing ranges are: $r_1 = 10m$, $r_2 = 12m$, $r_3 = 15m$, $r_4 = 20m$, $r_5 = 30m$, and $r_6 = 60m$. Figure 4 shows the simulation results for our two different heuristics. Figure 4 (a) is the result produced by the virtual backbone based algorithm, while Figure 4(b) shows the result produced by the coverage based algorithm. In this experiment, 100 targets are randomly distributed in a $130m \times 130m$ field. We vary the number of sensors from 80 to 180 with an increment of 10 and set the transmission usage ratio $\beta = 0.2$. The other environment parameters include initial energy 10 and transmission range 25m. Simulation results indicate that adjustable sensing ranges have great impact on network lifetime. If the maximal sensing range is fixed, the more adjustable sensing ranges, the higher the network lifetime. Thus, adjustable sensing ranges have direct influence on increasing network lifetime. Comparing Figure 4(a) and Figure 4(b), we find the virtual backbone based heuristic and the coverage based heuristics show similar performance under all adjustable sensing range schemes. Moreover, the more the adjustable sensing ranges are, the steeper the curves in Figure 4 become. That is, with the same number of sensors, the network with more adjustable sensing ranges will have a longer lifetime.



(a) (b)

Fig. 4. The effect of adjustable sensing ranges on network lifetime

In Figure 5 we observe the network lifetime under different unit time slot assumptions. Again, we evaluate the impact of unit time slots with both the virtual backbone based (VBB) algorithm and the coverage based (CB) algorithm. We measure the network lifetime under the condition that the number of sensors range from 80 to 180 with an increment of 10 and 100 targets. In the network to be evaluated, each sensor has 3 sensing ranges with values $20m$, $40m$, and $60m$. Both sensing energy consumption and transmission energy consumption are quadratic. In Figure 5(a), we test two different unit time slots, $d = 0$ and $d = 0.25$ for both the VBB algorithm and the CB algorithm. Note $d = 0$ represents the ideal case (no transmission delay). Because the two algorithms show approximately the same properties under the ideal case ($d = 0$) and non-ideal case ($d = 0.25$), we compare the effect of different values of unit time slot only with the virtual backbone based algorithm. In Figure 5(b), we test d with values of 0.25, 0.5, 0.75, and 1. Besides these parameters, we set the transmission usage ratio $\beta = 0.2$ and initial energy $E = 10$.

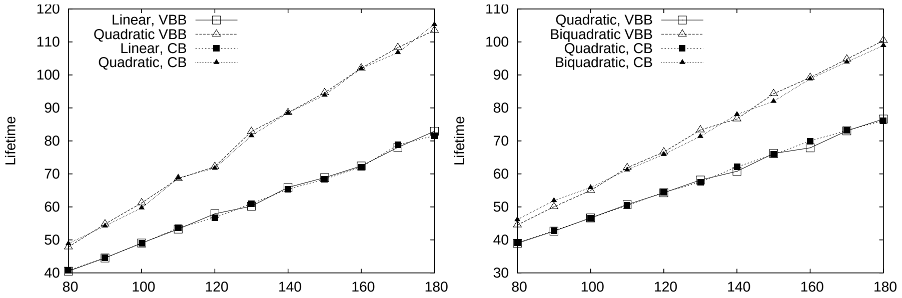


(a) (b)

Fig. 5. The effect of unit time on network lifetime

Network lifetime produced by the algorithm with lower unit time is longer than the one with higher unit time. This happens because, in our distributed heuristic algorithms, breaking a tie is at the expense of back-off time, and there is also no guarantee of avoiding conflict. A conflict occurs when the time between any two sensors' broadcast is less than d. Then, there might be sensors that work instead of going to the sleep state, even if the targets within their sensing ranges have already been covered. As illustrated in Figure 5 (a) and (b), the transfer delay also affects the network lifetime. The longer the transfer delay, the shorter the lifetime.

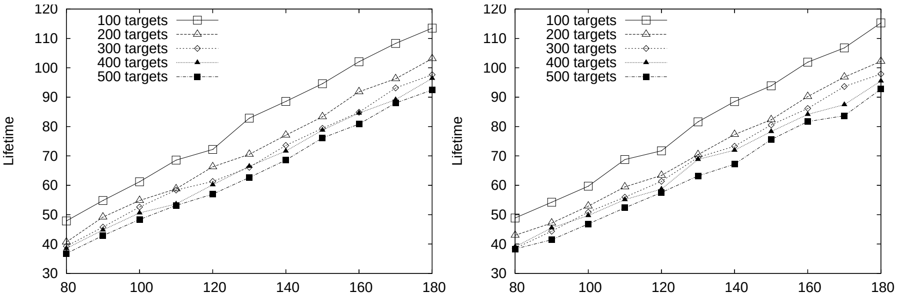
In Figure 6, we study the impact of different energy models on network lifetime when the number of sensors ranges from 80 to 180 with increments of 10. The number of targets is set to be 100. In the networks, each sensor has $P = 3$ sensing ranges with values $20m, 40m,$ and $60m.$ In Figure 6(a), we compare the linear energy model ($e_p = c_s \cdot r_p$) with the quadratic energy model ($e_p = c_s \cdot r_p^2$) for sensing energy consumption. Initial energy $E = 10$, the transmission usage ratio is set to be $\beta = 0.2$, the transmission range is $25m$, and the transmission energy model is quadratic. The simulation results show that the lifetime is longer in the quadratic model than in the linear model for both heuristics. Figure 6(b) shows the result with different transmission energy models. We compare the quadratic energy model ($g_e = \beta \cdot c_t \cdot d_c^2$) with the biquadratic energy model ($g_e = \beta \cdot c_t \cdot d_c^4$) under the condition of quadratic sensing energy model. The results tell us the biquadratic energy model has longer network lifetime than the quadratic energy model.



(a) (b)

Fig. 6. The effect of energy models on network lifetime

We also study the effect of the number of targets on network lifetime. Again, we increase the number of sensors from 80 to 180 with an increment of 10. Also, each sensor has $P = 3$ sensing ranges with values: $20m, 40m,$ and $60m.$ The energy model for both sensing energy and transmission energy is quadratic, the initial energy is 10, and the transmission usage ratio is $\beta = 0.2$. We evaluate this metric both for the CB heuristic and VBB heuristic, as shown in Figure 7(a) and 7(b) respectively. The number of targets changes from 100 to 500 with an increment of 100. Figure 7 shows the simulation results. Figure 7(a) was produced with the VBB algorithm, while Figure 7(b) demonstrate the CB algorithm. The simulation results show that the network lifetime will decrease as the target number increases. It is because additional targets require more sensors to monitor. Again, the two heuristics make no big difference in this experiment.



(a) (b)

Fig. 7. The effect of the number of targets on network lifetime

Figure 8 is the result of our experiment on the effect of transmission range on network lifetime. In the experiment, we change the amount of sensors from 400 to 500 with an increment of 10. In order to guarantee network connectivity, we use a larger number of sensors in this experiemnt than in the other experiments. In the network, each sensor has 3 sensing ranges with the values $20m, 40m,$ and $60m$. The energy model for both sensing energy and transmission energy is quadratic, the initial energy is 10, the transmission usage ratio β equals 0.2, and the number of targets is 200. We use the coverage based algorithm to evaluate the performance. The transmission range varies from 10 to 30 with an increment of 5. The simulation result shows that the network lifetime decreases with an increase of transmission range. It is because a larger transmission range consumes more energy.

Figure 9 is the result of our experiment on the effect of transmission usage ratio β on network lifetime. In this experiment, we test three cases, including two extremes: transmission and sensing have a similar frequency($\beta = 1$) and transmission is much lower than sensing ($\beta = 0.01$). The third case is $\beta = 0.5$, which is in the middle of the two extreme cases. We increase the number of sensors from 80 to 180 with an increment of 10. Each sensor has $P = 3$ sensing ranges with values $20m, 40m,$ and $60m$. The energy model for both sensing energy and transmission energy is quadratic, the initial energy is 10, and the number of targets is 200. We use the coverage based algorithm to evaluate the performance. We set the transmission range to be 25. The simulation results show that the network lifetime decreases with each increment of transmission usage ratio. It is because a larger transmission usage ratio consumes more energy.

In Figure 10, we give an example of an active sensor set in a round produced by the virtual backbone based heuristic. We assume a 100×100 area, with 40 sensors and 25 targets. We use a quadratic energy model for both sensing energy and transmission

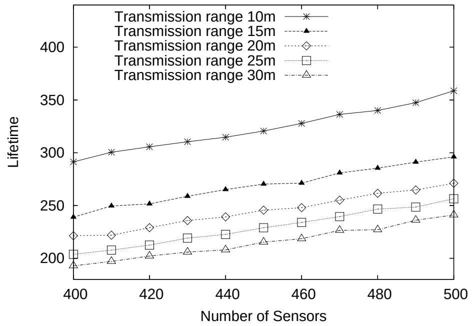


Fig. 8. The effect of transmission range on network lifetime

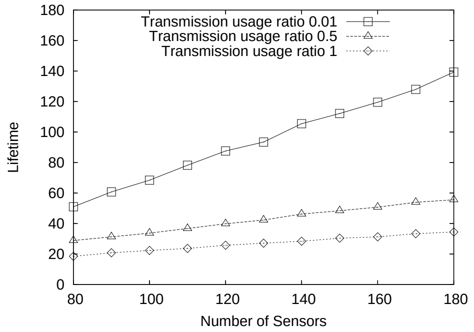
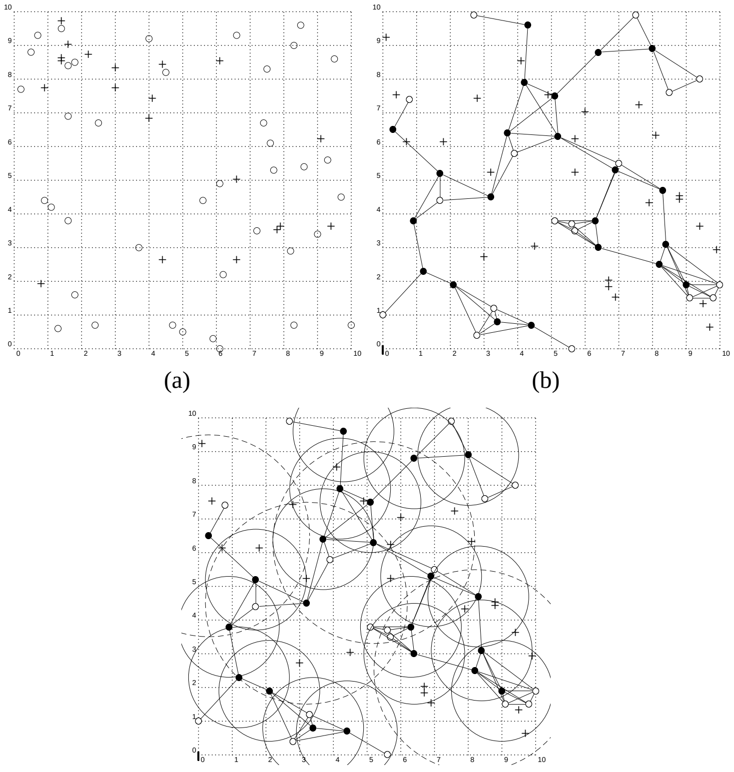


Fig. 9. The effect of transmission usage ratio on network lifetime

energy. The first graph represents the random deployment of sensors and targets. The transmission range d_c is $25m$. If the distance between any two sensor nodes is no more than d_c, we connect these two sensors by a undirected link. Thus a connected graph is constructed, as shown in 10 (b). Notice that the active sensors are blackened. Each sensor has $P = 2$ sensing ranges with values $15m$ and $30m$. We use solid lines to represent $r_1 = 15m$ and dashed lines for $r_2 = 30m$. Figure 10(d) shows the schedule satisfying both connectivity and coverage. Note the line type indicates the sensing range value.

In Figure 11, we present another example of an active sensor set resulting from the coverage based heuristic. In this case, we deploy 80 sensors and 100 targets in a 100×100 area. The energy model is quadratic, for each sensor there are 2 adjustable sensing ranges, whose values are $10m$ and $20m$, and the transmission range is $20m$. Figure 11 (a) is the initial deployment. Figure 11 (b) is the result of the coverage phase, in which all targets are covered but active sensors (black nodes) do not satisfy the connectivity property. By applying Rule-k, active sensors are connected together, as shown

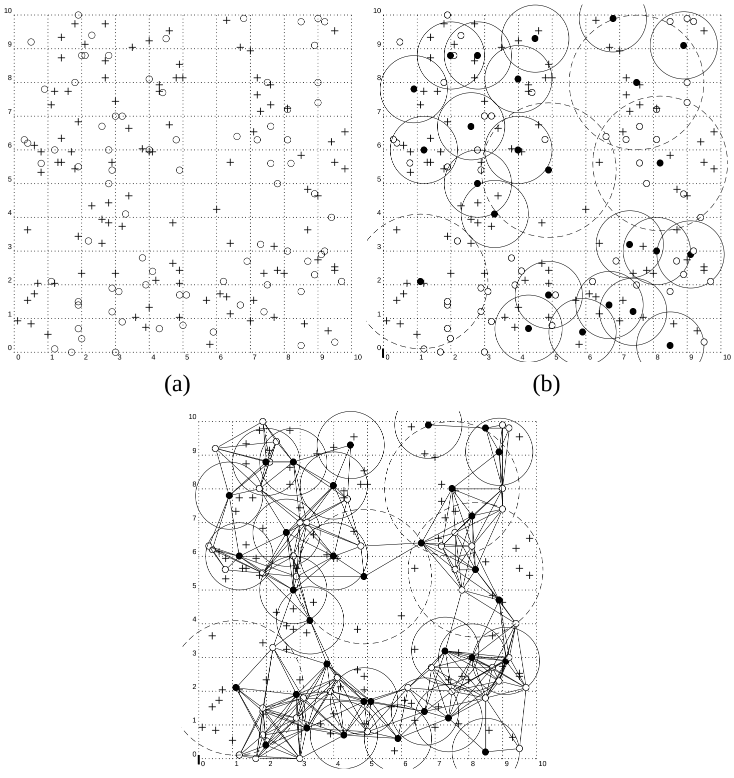


(a) (b)

(c)

Fig. 10. Set coverage example by virtual backbone based heuristic, where each ″○″ is a sensor and each ″+″ is a target. (a) Deployment of sensors and targets. (b) Connected dominating set (black nodes) selected by Connectivity Initialization. (c) Connected coverage (black nodes are active sensors).

in Figure 11 (c), in which active sensors (including sensors for coverage as well as only for connectivity) are all blackened.



(a) (b)

(c)

Fig. 11. Set coverage example by coverage based heuristic, where each ″○″ is a sensor and each ″+″ is a target. (a) Deployment of sensors and targets. (b) Active sensors satisfying coverage but not connected (black nodes) selected by coverage process. (c) Connected coverage (black nodes are active sensors).

6 Conclusions

In this paper, we study the problem of maximizing a WSN's lifetime (in terms of rounds) while maintaining both discrete target coverage and network connectivity. This not only provides satisfactory quality of service in WSNs, but also presents more options and challenges to design an energy-efficient sensor scheduling. We study the relationship between network connectivity and target coverage and introduce a generic condition to guarantee network connectivity. We design two round-based distributed algorithms to coordinately determine each sensor' sensing range based on different relations between transmission range and maximal sensing range.

In the future, we will study the impact of the degree of coverage on network lifetime and its relationship with network connectivity. We will also take into account the communication cost and its impact on network lifetime.

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