Event-driven Partial Barriers in Wireless Sensor Networks

Hyunbum Kim*, Junggab Son†, Hyung Jae Chang‡, Heekuck Oh§

*Department of Computer Science, University of North Carolina at Wilmington, Wilmington, NC 28403, USA
kimh@uncw.edu
†Department of Mathematics and Physics, North Carolina Central University, Durham, NC 27707, USA
json@nccu.edu
‡Department of Computer Science, Troy University at Montgomery, Montgomery, AL 36104, USA
hjchang@troy.edu
§Department of Computer Science and Engineering, Hanyang University, Ansan, South Korea
hkoh@hanyang.ac.kr

Abstract—Recently a barrier-coverage in wireless sensor networks (WSN), which detects a moving object from one side to another opposite side, has attracted lots of attention. Although it is highly desirable to consider a barrier-coverage which can detect any moving objects for multiple sides simultaneously in event-driven environment, an existing barrier does not support those properties. In this paper, we introduce a new type of barrier, event-driven partial barrier, which can detect or monitor every movement of mobile objects on paths among multiple hubs in event-driven environment. Based on the new barrier concept, we define k-EP barriers that a motion by mobile objects is guaranteed to be detected by at least k sensors. Also, we formally define a problem whose objective is to minimize the number of sensors in order to construct k-EP barriers for every hub. To solve the problem, we propose two novel approaches to maximize a network lifetime by minimizing the number of sensors with satisfying requirements of k-EP barriers. Then, we evaluate their relative performances through extensive simulations.

I. INTRODUCTION

A wireless sensor networks (WSN) has attracted lots of attention during recent years because it can be used for numerous applications such as battlefield surveillance, machine health monitoring, environmental monitoring [1], [2]. WSN consists of a large number of sensors, which each sensor is a tiny device with low-power. A coverage, which is one of the most critical issues in a WSN, is largely classified into two categories: full-coverage and partial-coverage. In full-coverage, it can monitor full area of interest at any moment [3], [4], [5]. On the contrary, partial-coverage does not cover a whole area and so it may miss some events [6], [7].

Recently, a special coverage form of partial-coverage, known as barrier-coverage, has been one of key research issues in WSN because it is appropriate for various important applications, such as intrusion detection, border surveillance [8], [9], [10]. A subset of sensors can construct a barrier over an area of interest and a penetration from one side to another opposite side is guaranteed to be detected by at least one sensor in the barrier. When compared against full-coverage, barrier-coverage has an advantage of saving the number of sensors which are necessary to detect such a penetration into the area.

It is highly desirable to consider barriers which can detect any moving objects among multiple end-locations or hubs in event-driven environment. Such a barrier in the event-driven environment has several properties: (i) The set of considered multiple hubs can be changed often. (ii) To satisfy a specific objective of applications, a construction of barriers can be changed whenever a new event occurs or a new hub is added to the network. (iii) Every barrier should always meet requirements of the pursuing application. To the best of our knowledge, previous studies do not provide those barriers of event-driven environment.

To increase a network lifetime with those barriers, it is reasonable to use sleep-wakeup schedule [8], [10]. A sensor node will be converted as a sleep-mode if it is not a part of barriers for current hubs and it will be also active when an event occurs. Moreover, the network lifetime of barriers can depend on the number of sensors which are necessary to generate the required barriers. Therefore, if we reduce the number of sensor nodes to satisfy barrier coverage requirements, the total network lifetime can be maximized.

Based the above motivations, we introduce a new framework of barriers, event-driven partial barrier-coverage, such that any moving objects on paths can be detected between hubs in an event-driven environment. Based on the new barrier-coverage concept, we present k-event-driven partial barriers, referred as k-EP barriers, which any movement is guaranteed to be detected by at least k different sensors among hubs. Also, we formally define a problem whose objective is to minimize the number of sensors to form k-EP barriers in the event-driven environment.

This paper is organized as follows. Next, we review related works for barrier-coverage of WSN. In Section III, we present a more formal description of event-driven partial barriers and define a new problem for k-EP barriers, followed in Section IV by two approaches we propose for the construction of these barriers. Then, in Section V, we analyze the performances of developed approaches through extensive simulations. Finally, we conclude this paper in Section VI.
II. RELATED WORK

A concept of barrier-coverage was firstly introduced by Gage [11] who considered the network for robotic sensors. In [8], Kumar et al. introduced the notion of $k$-barriers, which is a generalization of barrier-coverage in a sense that at least $k$ different sensor nodes can detect an intruder’s penetration which moves from one side to the other side. In [10], Kumar et al. studied a sleep-wakeup scheduling problem for $k$-barriers of wireless sensors. In order to maximize the network lifetime to protect an area of interest, they considered use of sleep-wakeup schedule which activate barrier-covers alternatively. Then, they proposed an optimal sleep-wakeup algorithm called Stint to provide $k$-barrier-coverage. Later, Ban et al. developed a distributed algorithm for this problem, which works with low communication overhead and computation cost, and therefore is appropriate for large scale WSN [12]. In [13], authors introduced a reinforced barrier-coverage which can detect any movement variation of the intruder.

III. EVENT-DRIVEN PARTIAL BARRIERS

In this section, we introduce a new type of sensor barrier. Also, we define our problem formally. Then, we describe how to construct the new type of barriers to solve the problem.

A. A New Type of Sensor Barrier

Let us consider an application monitoring the volume of traffic or monitoring the delivery by mobile drones among interested hubs in a given area and current active hubs can be changed or added to the area frequently. Assume that each city is considered as each hub and all sensors are deployed randomly in the given area. Also, let us assume we can find possible node-disjoint paths between two hubs, which each path between those hubs consists of a set of sensors. Now, in this event-driven environment, we want to check movements of vehicles or mobile drones between city $A$ and $B$. Simultaneously, we also would like to monitor the volume of traffic between city $C$ and $D$ and movements between city $E$ and $F$. To do so, it is necessary to construct barriers which can detect all movements on paths from one hub to another hub simultaneously. Whenever an event occurs in the system, (i.e. changing a hub location or adding a new hub), a system should be able to detect or monitor all movements of objects among hubs by constructing those barriers.

Consider that $n = 42$ sensor nodes are deployed randomly in the square-shaped area and we have a set of hubs $H = \{h_1, h_2, h_3, h_4, h_5, h_6\}$ initially. Now, assume that there are three hub pairs: $H_{1,2}$, $H_{3,4}$, $H_{5,6}$. (i.e. $H_{1,2} = \{h_1, h_2\}$). Then, for each pair, we can search for different node-disjoint paths. Suppose that we have four node-disjoint paths for $H_{1,2}$ and three paths for $H_{3,4}$, $H_{5,6}$, respectively. Now, mobile objects can move between two hubs through those disjoint paths. Fig. 1(a) shows the initial status. In Fig. 1(a), each triangle represents a hub and a black circle is represented as a sensor node. Possible node-disjoint paths for each hub pair are described as dotted lines. Each sensor on the node-disjoint path should be connected if two sensors $s_1$ and $s_2$ can communicate with each other using transmission range $r$, which is the euclidian distance between two sensors $\text{EucDist}(s_1, s_2) \leq 2 \cdot r$.

For all node-disjoint paths between hubs, if we can find a formation that all node-disjoint paths in a hub pair are connected by sensors such that only one sensor per a node-disjoint path is selected in the formation, then we define this formation of sensors as event-driven barriers for a hub pair, which is simply referred as $e$-barrier. Also, it is defined that the network supports $k$-event-driven partial barriers if $k$ numbers of event-driven barriers can be constructed for every hub pair. In Fig. 1(b), solid lines represent the construction of $k$ numbers of event-driven barriers for current hub pairs. The constructed
barriers are composed of 26 number of sensors. It follows that all movements of objects on paths among hub pairs can be detected by at least $k$ sensors in the constructed barriers.

Now, we are ready to present the formal definition of an event-driven partial barriers.

**Definition 3.1 (Event-driven Partial Barriers):** Given a set of wireless sensor nodes $S$ and a set of hubs $H$ deployed over an square-shaped area $A$, a event-driven partial barrier is a combination of event-driven barriers for each hub pair. And $k$-event-driven partial barriers, referred as $k$-EP barriers, guarantee that at least $k$ sensor nodes can detect any movement of objects on paths for every hub pair.

**B. Problem Definition**

We consider a square area, $A$, where a set of sensors, $S$ with size $n$, have been randomly deployed. The location of each sensor is fixed after its deployment. Also, there exists a set of interested hubs, $H$ with size $m$ within a square area $A$. The set of hubs can be changed frequently within area $A$. Each sensor can be either in sleep mode, in which case it uses a negligible amount of power, or in service mode, in which it senses its environment. When a sensor is used as any part of active barriers, sensor is in service mode. Otherwise, sensors basically become a sleep mode to save their batteries. All sensors are assumed to have an equal amount of power, and thus, an equal lifetime. For simplicity, we also assume that all sensors have the same communication range, which we denote by $r$.

Two sensors, $s_1$ and $s_2$, are said to be neighbors and to be connected if the euclidian distance between them is at most $2 \cdot r$. A node-disjoint path is a sequence of sensors, $s_1, s_2, \ldots, s_k$, between two hubs $h_i, h_j \in H_{i,j}$ where:

- $s_p$ and $s_{p+1}$ are neighbors, $1 \leq p < n$.
- $s_1$ is a neighbor of $h_i$ and $s_k$ is a neighbor of $h_j$.
- $1 \leq i, j \leq m$ and $1 \leq k \leq n, i \neq j$

There may have several node-disjoint paths for a hub pair $H_{i,j}$. That is, there exists a node-disjoint path set $P_{H_{i,j}} = \{p_1, p_2, \ldots, p_a\}$ between a hub pair $H_{i,j}$, where $1 \leq a \leq n - 1$.

Several $e$-barriers also can be found per a hub pair. So, for a hub pair $H_{i,j}$, there exists a set of $e$-barriers, $E_{i,j} = \{e_1, e_2, \ldots, e_k\}$ where $1 \leq b \leq n - 1$. Each $e$-barrier in $E_{i,j}$ is an independent one and is constructed as a sequence of connected sensors, $s_1, s_2, \ldots, s_a$, where $s_1 \subseteq p_1, s_2 \subseteq p_2, \ldots, s_a \subseteq p_a$. And a sensor $s_i$ in the sequence should be connected by another sensor $s_{i+1}$ in the sequence, where $i < a$.

Our problem is defined formally as follows.

**Definition 3.2 (MinSkEP):** Given a set of wireless sensor nodes $S$ and a set of hubs $H$ deployed over an square-shaped area $A$, the minimum number of sensors for $k$-EP barriers (MinSkEP) problem is to minimize the number of sensor nodes to construct $k$-EP barriers which can detect movements of objects among given hubs.

**IV. PROPOSED HEURISTICS**

In this section, we present our two approaches to solve our MinSkEP problem.

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**Algorithm 1 Initial-Setup**

**Inputs:** $S, H, r, k$

1. find a node-disjoint path set $P_{H_{i,j}}$ for each hub pair $H_{i,j}$;
2. find an $e$-barrier set $E_{i,j}$ for each $H_{i,j}$;
3. set a frequency of each sensor shared by different $e$-barriers: $f_i = 0$;
4. for each sensor $s_i$, check whether $s_i$ is used as $e$-barrier in a different hub pair;
5. if there exists then
6. increase a frequency of the sensor: $f_i++$;
7. end if

As an initial stage, we perform the following two steps to find possible node-disjoint paths $P_{H_{i,j}}$ for each hub pair (i.e. from $h_i$ to $h_j$).

**Step 1.**

Create a flow graph $G = (V(G), E(G))$, as follows.

- For each sensor $s \in S$, include two vertices in $V(G)$, $s_{in}$ and $s_{out}$.
- For each sensor $s \in S$, add a directed edge $(s_{in}, s_{out})$ to $E(G)$.
- For every pair of sensor nodes $s$ and $t$ in $S$ that are neighbors, add the following two directed edges to $E(G)$: $(s_{out}, t_{in})$, $(t_{out}, s_{in})$.
- Add hubs $h_i$ and $h_j$ to $V(G)$.
- For each neighbor $s$ of $h_i$, add an edge $(h_i, s_{in})$ to $V(G)$.
- For each neighbor $s$ of $h_j$, add an edge $(s_{out}, h_j)$ to $V(G)$.

**Step 2.**

Assign a capacity of 1 to each edge in the flow graph, and run a maximum flow algorithm, such as Edmonds-Karp algorithm [14], from $h_i$ to $h_j$. Edges with a flow of 1 will form disjoint paths from $h_i$ to $h_j$. All other edges will have a flow of 0.

As the second initial stage, we then find a set of $e$-barriers, $E_{i,j} = e_1, e_2, \ldots, e_k$, where $1 \leq b \leq n - 1$ for every hub pair $H_{i,j}$. Each $e$-barrier within a hub pair is an independent one. For instance, the sensors in $e_1$ cannot be used at $e_2$. Then, as the third initial stage, a sensor frequency that is the number of times used in constructed $e$-barriers, is calculated for each sensor. The pseudocode for above stages is presented in Algorithm 1, which we call as Initial-Setup. Whenever events occur such as an appearance of new hubs, Initial-Setup will be performed.

**A. Approach 1**

Based on the results by Initial-Setup, approach 1 returns $EP$ which is the number of sensors consisting of $k$-EP barriers. The steps of approach 1 are as follows.

- Find $e$-barrier $e_{max}$ with the maximum number of shared sensors by other $e$-barriers.
- Search for $e$-barriers including sensors which are in the found $e_{max}$.
- Activate the found $e$-barriers including $e_{max}$ as $k$-EP barriers.
Algorithm 2 Greedy-Shared-Barrier

Inputs: $S, H, r, k$, Output: $EPS$

1: set the number of sensors consisting of $k$-EP barriers: $EPS = 0$;
2: call Algorithm 1 for Initial-Setup;
3: while $k$-EP barriers are not constructed do
4: set a set of current activated $e$-barriers: $E_{act} = \emptyset$;
5: set a sensor set which is covered by $E_{act}$: $S_{act} = \emptyset$;
6: find $e$-barrier $e_{max}$ with the largest number of shared sensors by other $e$-barriers;
7: activate $e_{max}$ and also active $e$-barriers which are affected by sensors in $e_{max}$;
8: add both $e_{max}$ and the activated $e$-barriers to $E_{act}$;
9: update $E_{act}$ to $k$-EP barriers;
10: find $S_{act}$ which is covered by $E_{act}$;
11: calculate the number of sensors of $S_{act}$: $Num_{S_{act}}$;
12: update $EPS = EPS + Num_{S_{act}}$;
13: if $k$-EP barriers are constructed then
14: break;
15: end if
16: end while
17: return $EPS$

- Find a sensor set $S_{act}$ which is covered by the found $e$-barriers and then calculate the size of $S_{act}$.
- Update $EPS$ by adding the size value of $S_{act}$.

The above steps are iterated until we construct $k$-EP barriers completely. The pseudocode is presented in Algorithm 2 in more detail, which we call as Greedy-Shared-Barrier.

B. Approach 2

Before finding $k$-EP barriers, approach 2, which we referred as Greedy-Shared-Sensor, also implements Initial-Setup similar to approach 1. To construct $k$-EP barriers, our approach 2 does the following steps iteratively.

- Find a sensor $s_{max}$ with the largest frequency, which is a sensor shared by $e$-barriers.
- Search for $e$-barriers that include $s_{max}$ and activate the found $e$-barriers as $k$-EP barriers.
- Find a sensor set $S_{act}$ which is contained in the activated $e$-barriers and then calculate the size of $S_{act}$.
- Update $EPS$ by adding the size value of $S_{act}$.

The above steps are repeated until $k$-EP barriers are generated finally in the network. The pseudocode is described in Algorithm 3 in more detail.

V. EXPERIMENTAL EVALUATION

In this section, we evaluate and discuss performances of the two approaches in Section IV. We have simulated various experiments in a square-shaped area of size $500 \times 500$ m$^2$ where both a set $S$ of sensor nodes and a set $H$ of hubs are randomly deployed in the two-dimensional area initially. Each experiment represents the average result of 100 different graphs. The number of sensors which have used is 100 and the number of hub points are ranging from 4 to 14. Also, a communication range of sensor, $r$, is ranging from 50 to 60 in our experiments. If $e$-barriers by an initial graph can not be generated using given parameters, we re-created the graph with different sensors and hub points locations by deploying them randomly in a given area. Through various simulations, we have checked that Greedy-Shared-Sensor outperforms Greedy-Shared-Barrier as a whole. Now, we evaluate the results by two different scenarios.

In our first experiment, we compare Greedy-Shared-Barrier and Greedy-Shared-Sensor for the number of sensors $EPS$ to construct $k$-EP barriers. Fig. 2 shows results for the proposed approaches with $k = 1$ for $k$-EP barriers by different sensor radius $r = 50, 55$ and $60$, respectively. Basically, as the number of hub points increases, $EPS$ increases for both approaches as shown in Fig. 2. In this simulation, we have checked that Greedy-Shared-Sensor shows better results than Greedy-Shared-Barrier.

In the second scenarios, we consider another case: $k = 2$ with different radius $r = 50, 55$ and $60$. Compared with the first experiment with $k = 1$, we could verify that the constructed $k$-EP barriers require more sensor nodes than the first simulation because each hub pair needs to maintain the reinforced $k$-EP barriers as $k = 2$. Also, Fig. 3 represents Greedy-Shared-Sensor shows slightly better results than Greedy-Shared-Barrier.

VI. CONCLUDING REMARKS

In this paper, we introduced a new type of barriers, $k$-EP barriers, which at least $k$ sensors can detect all movements of objects among hubs in event-driven environment. Also, we defined a new problem whose objective is to minimize the number of sensors such that $k$-EP barriers are constructed. To solve the problem, we proposed two different approaches to generate $k$-EP barriers. Then, we evaluated their performances through extensive simulations.

Algorithm 3 Greedy-Shared-Sensor

Inputs: $S, H, r, k$, Output: $EPS$

1: set the number of sensors consisting of $k$-EP barriers: $EPS = 0$;
2: call Algorithm 1 for Initial-Setup;
3: while $k$-EP barriers are not constructed do
4: set a set of current activated $e$-barriers: $E_{act} = \emptyset$;
5: set a sensor set which is covered by $E_{act}$: $S_{act} = \emptyset$;
6: find a sensor $s_{max}$ with the largest frequency $f_{max}$;
7: activate $e$-barriers which are affected by $s_{max}$ and add them to $E_{act}$;
8: add $E_{act}$ to $k$-EP barriers;
9: find $S_{act}$ which is covered by $E_{act}$;
10: calculate the number of sensors of $S_{act}$: $Num_{S_{act}}$;
11: update $EPS = EPS + Num_{S_{act}}$;
12: if $k$-EP barriers are constructed then
13: break;
14: end if
15: end while
16: return $EPS$
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