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 event [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.

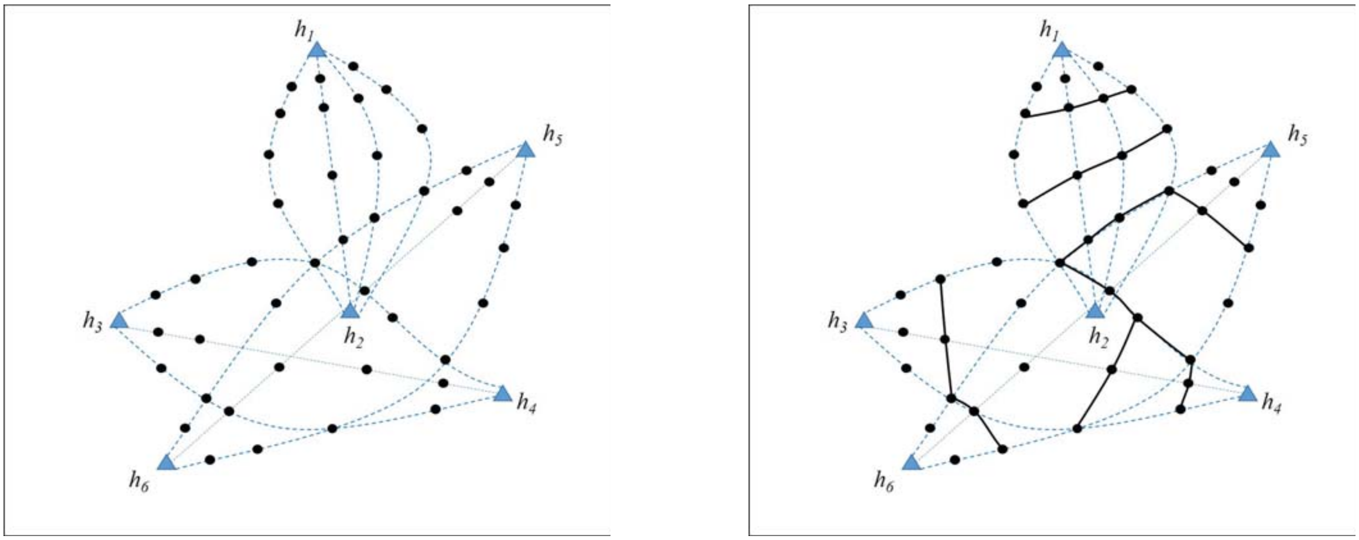
It is highly desirable to consider barriers which can detect any moving objects among multiple end-locations or hubs in event-driven environment. Such a barrier in the event-driven environment has several properties: (i) The set of considered multiple hubs can be changed often. (ii) To satisfy a specific 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.

978-1-4673-8579-4/16/$31.00 ©2016 IEEE



(a) Initial status

(b) Construction of event-driven partial barriers with k = 3

Fig. 1. Possible formation of event-driven partial barriers with k = 3.

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 scheduling 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 $EucDist(s_1, s_2) \leq 2 \cdot r$.

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 a *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, $1 \leq p \leq n-1$.
- 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 $P_{H_{i,j}} = p_1, p_2, ..., p_a$ 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, $E_{i,j} = e_1, e_2, ..., e_b$ 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 $s_1 \in p_1, s_2 \in p_2, ..., s_a \in p_a$. 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.

Algorithm 1 ***Initial-Setup***
Inputs: S, H, r, k

```
find a node-disjoint path set P_{H_{i,j}} for each hub pair H_{i,j};
find a e-barrier set E_{i,j} for each H_{i,j};
set a frequency of each sensor shared by different e-barriers: f_i = 0;
for each sensor s_i, check whether s_i is used as e-barrier in a different hub pair;
if there exists then
   increase a frequency of the sensor: f_i++;
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* $\mathcal{G} = (V(\mathcal{G}), E(\mathcal{G}))$, as follows.

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

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, $E_{i,j} = e_1, e_2, ..., e_b$ 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 can not 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 EPS 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

set the number of sensors consisting of k-EP barriers: $EPS = 0$;
call Algorithm1 for Initial-Setup;
while k-EP barriers are not constructed **do**
    set a set of current activated e-barriers: E_{act} = $\emptyset$;
    set a sensor set which is covered by E_{act}: S_{act} = $\emptyset$;
    find e-barrier e_{max} with the largest number of shared sensors by other e-barriers;
    activate e_{max} and also active e-barriers which are affected by sensors in e_{max};
    add both e_{max} and the activated e-barriers to E_{act};
    add E_{act} to k-EP barriers;
    find S_{act} which is covered by E_{act};
    calculate the number of sensors of S_{act}: $Num_{S_{act}}$;
    update EPS = EPS + $Num_{S_{act}}$;
    if k-EP barriers are constructed **then**
        break;
    end if
end while
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.

Algorithm 3 ***Greedy-Shared-Sensor***

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

set the number of sensors consisting of k-EP barriers: $EPS = 0$;
call Algorithm1 for Initial-Setup;
while k-EP barriers are not constructed **do**
    set a set of current activated e-barriers: E_{act} = $\emptyset$;
    set a sensor set which is covered by E_{act}: S_{act} = $\emptyset$;
    find a sensor s_{max} with the largest frequency f_{max};
    active e-barriers which are affected by s_{max} and add them to E_{act};
    add E_{act} to k-EP barriers;
    find S_{act} which is covered by E_{act};
    calculate the number of sensors of S_{act}: $Num_{S_{act}}$;
    update EPS = EPS + $Num_{S_{act}}$;
    if k-EP barriers are constructed **then**
        break;
    end if
end while
return EPS

V. Experimental Evaluation

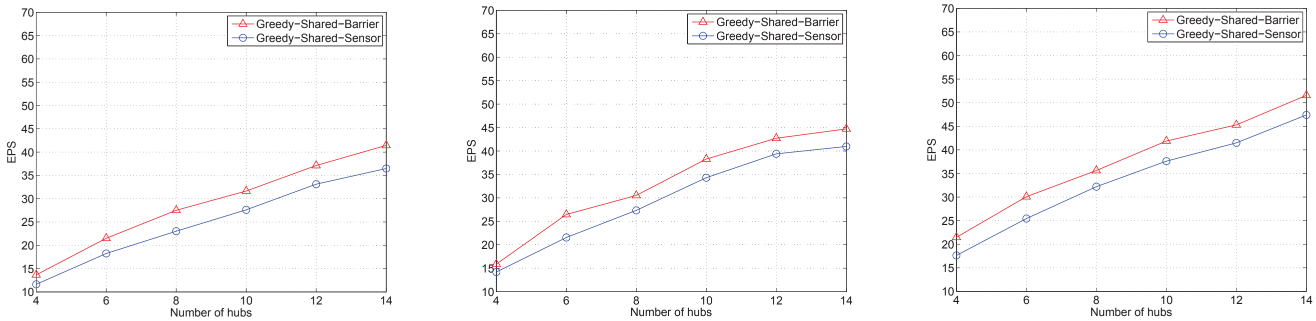
In this section, we evaluate and discuss performances of the two approaches in Section IV. We have simulated various experiments in a square-shaped area of size 500 $\times$ 500 m^2 where both a set S of sensor nodes and a set H of hubs are randomly deployed in the two-dimensional area initially. Each 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*.

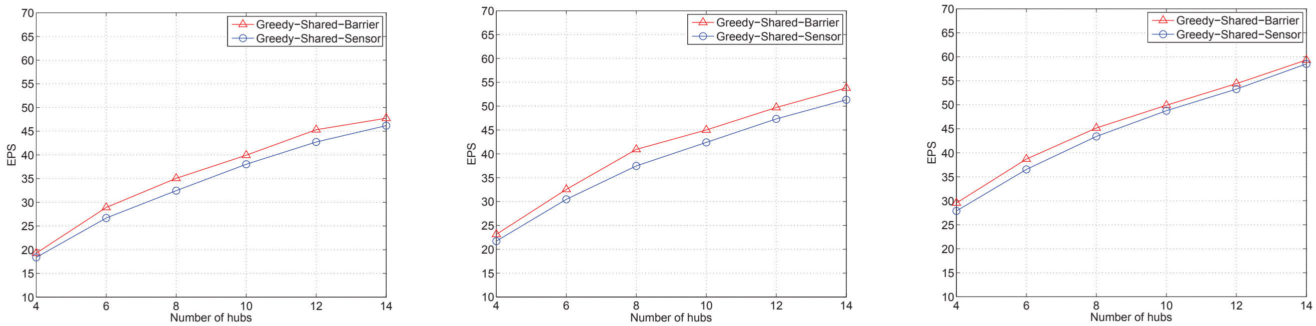
VI. Concluding Remarks

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.



(a) r = 50 with k = 1 (b) r = 55 with k = 1 (c) r = 60 with k = 1

Fig. 2. Comparison of EPS for different sensor communication rage r with k = 1 by *Greedy-Shared-Barrier* and *Greedy-Shared-Sensor*



(a) r = 50 with k = 2 (b) r = 55 with k = 2 (c) r = 60 with k = 2

Fig. 3. Comparison of EPS for different sensor communication rage r with k = 2 by *Greedy-Shared-Barrier* and *Greedy-Shared-Sensor*

ACKNOWLEDGEMENT

This research was supported in part by UNCW travel fund of professional activity. Also, this research was supported in part by the MSIP (Ministry of Science, ICT and Future Planning), Korea, under the ITRC (Information Technology Research Center) support program (IITP-2015-H8501-15-1018 and IITP-2015-H8501-15-1007) supervised by the IITP (Institute for Information and communications Technology Promotion).

REFERENCES

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless Sensor Networks: a Survey," *Computer Networks*, vol 38, issue 4, pp. 393-422, March, 2002.

[2] J. Yick, B. Mukherjee, and D. Ghosal, "Wireless Sensor Network Survey," Computer Networks, vol. 52, issue 12, pp. 2292-2330, August, 2008.

[3] C. Huang and Y. Tseng, "The Coverage Problem in a Wireless Sensor Network," in *Proc. of ACM International Workshop on Wireless Sensor Networks and Applications (WSNA)*, 2003.

[4] H. Zhang and J. Hou, "On Deriving the Upper Bound of α-lifetime for Large Sensor Networks," in *Proc. of the ACM International Symposium on Mobile Ad-hoc Networking and Computing (MobiHoc)*, 2004.

[5] M. Cardei, M. Thai, Y. Li and W. Wu, "Energy-Efficient Target Coverage in Wireless Sensor Networks," *IEEE Annual International Conference on Computer Communications (INFOCOM)*, March, 2005.

[6] C.T. Vu, G. Chen, Y. Zhao, and Y. Li, "A Universal Framework for Partial Coverage in Wireless Sensor Networks," *IEEE International Performance Computing and Communications Conference (IPCCC)*, December, 2009.

[7] Y. Li, C. Vu, C. Ai, G. Chen, and Y. Zhao, "Transforming Complete Coverage Algorithms to Partial Coverage Algorithms for Wireless Sensor Networks," *IEEE Transactions on Parallel and Distributed Systems (TPDS)*, vol. 22, issue 4, pp. 695-703, 2011.

[8] S. Kumar, T.H. Lai, and A. Arora, "Barrier Coverage with Wireless Sensors," in *Proc. of the 11th Annual International Conference on Mobile Computing and Networking (MobiCom)*, pp. 284-298, 2005.

[9] A. Saipulla, C. Westphal, B. Liu, and J. Wang, "Barrier Coverage of Line-based Deployed Wireless Sensor Networks," in *Proc. of the 28th IEEE Conference on Computer Communications (INFOCOM)*, 2009.

[10] S. Kumar, T.H. Lai, M.E. Posner, and P. Sinha, "Maximizing the Lifetime of a Barrier of Wireless Sensors," *IEEE Transactions on Mobile Computing (TMC)*, vol. 9, no. 8, August, 2010.

[11] D. Gage. "Command control for many-robot systems," in *Proc. of the Nineteenth Annual AUVS Technical Symposium (AUVS-92)*, 1992.

[12] D. Ban, Q. Feng, G. Han, W. Yang, J. Jiang, and W. Dou, "Distributed Scheduling Algorithm for Barrier Coverage in Wireless Sensor Networks," in *Proc. of the 2011 Third International Conference on Communications and Mobile Computing (CMC)*, April, 2011.

[13] H. Kim, J. A. Cobb,"Maximum Lifetime Reinforced Barrier-coverage in Wireless Sensor Networks," in *Proc. of the 19th IEEE International Conference on Networks (ICON)*," 2013.

[14] J. Edmonds and R.M. Karp, "Theoretical Improvements in Algorithmic Efficiency for Network Flow Problems," *Journal of the ACM*, vol. 19, issue 2, pp. 248-264, 1972.