HeteRBar: Construction of Heterogeneous Reinforced Barrier in Wireless Sensor Networks

Hyunbum Kim and Jalel Ben-Othman

***Abstract*— Recently, a barrier-coverage has gained much interest due to potentiality of various applications. In this letter, we introduce a reinforced barrier-coverage in heterogeneous wireless sensor networks, which guarantees that any penetration variation of intruder is detected by at least one sensor with a consideration of heterogeneous sensors with different capabilities. Also, we formally define a problem whose objective is to maximize the lifetime of heterogeneous reinforced barriers and propose two novel approaches, including a creation of base graph. Then, the performances of the proposed schemes are analyzed through various scenarios.**

***Index Terms*— Barrier-coverage, reinforced, heterogeneous, sensor, lifetime.**

I. Introduction

DUE to boundless potential, wireless sensor networks (WSN) has been studied widely by many researchers. It can be used for various areas in science, industry, public service. WSN basically consists of a number of sensors, which each sensor has limited capabilities such as limited battery, limited computational ability. Whenever sensor nodes sense specific events in the given area, they send the information to base stations by possible multi-hop communication [1].

A coverage must be one of important issues in WSN [2]. Recently, *barrier-coverage*, has attracted much interest of researchers because it also can be used for critical applications such as border surveillance, border patrol, intrusion detection system [3], [4]. Kumar *et al.* [4] also introduced k-barrier-coverage which guarantees that at least k sensors can detect a penetration of the intruder from one side to another in the region of interest. Moreover, Kim and Cobb [5] and Kim *et al.* [6] introduced *reinforced barrier*, which is able to detect any penetration variation of intruders in homogeneous WSN.

However, it is highly desirable to consider that sensors in the network may have different capabilities since sensors have different burdens of works depending on their deployed locations, routing protocol, etc. Furthermore, each sensor may have different sensing ranges and communication ranges according to its residual energy resource. Hence, these properties should be taken into account in the design of sensor barrier.

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H. Kim is with the Department of Computer Science, University of North Carolina at Wilmington, Wilmington, NC 28403 USA (e-mail: kimh@uncw.edu).

J. Ben-Othman is with the Department of Computer Science, University of Paris 13, 93430 Villetaneuse, France (e-mail: jalel.ben-othman@univ-paris13.fr).

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Based on the above observations, we introduce a heterogeneous reinforced barrier to detect any penetration type of intruders in heterogeneous sensor networks. In the proposed system, we consider sensors with different sensing ranges and communication ranges. Then, we formally define a problem to maximize a lifetime of heterogeneous reinforced barrier such that every sensor in the constructed barrier by sensing ranges has a reachable path to at least one of base stations by their communication ranges. To solve the problem, we first generate a base graph and then propose two approaches to form maximum number of heterogeneous reinforced barrier.

The rest of the paper is organized as follows. The next section reviews related work. In Section III, we introduce our heterogeneous reinforced barrier-coverage with a formally defined problem. Also, we represent the proposed novel approach. In Section V, we evaluate the performance of the proposed scheme through various scenarios. Finally, we summarize the contributions of this study in Section VI.

II. Related Work

The barrier-coverage in robotic sensors was introduced by Gage [3] firstly. Then, Kumar *et al.* [4] introduced a concept of k-barriers which guarantees a penetration is detected by at least k sensors. They defined an optimal sleep-wakeup scheduling problem to maximize a lifetime of k-barriers. Li *et al.* [7] developed a weak-k-barrier coverage and derived a lower bound of the probability of weak k-barrier-coverage. Kim and Cobb [5] and Kim *et al.* [6] proposed a new type of sensor barriers which can monitor any penetrations of intruders.

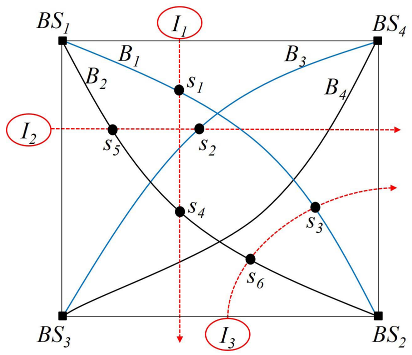
On the other hand, there exist several works for heterogeneous sensor networks. Lazos and Poovendran [8] and Lazos *et al.* [9] studied a problem of coverage in planar heterogeneous sensor networks. They considered the coverage problem with deployment of sensors by an arbitrary stochastic distribution.

III. Heterogeneous Reinforced Barrier

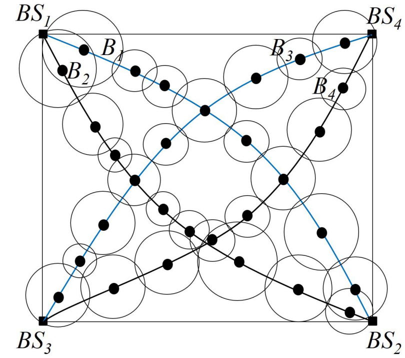
In this section, we introduce our heterogeneous reinforced barrier which is referred as *HeteRBar*. Then, we define a problem with Integer Linear Programming (ILP) formulation.

A. Heterogeneous Reinforced Barrier

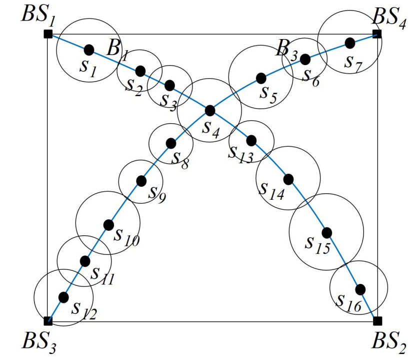
We consider a square-shaped area as region of interest (ROI). That is, ROI is the two-dimensional area which should be monitored. Four base stations, BS_1, BS_2, BS_3, BS_4, are located at each corner of the square area. Assume that initially n number of sensors, $S = \{s_1, s_2, \ldots, s_n\}$, are deployed



(a) Reinforced barriers in homogeneous sensors



(b) Construction of heterogeneous reinforced barriers by different sensing ranges



(c) Heterogeneous reinforced barrier by different communication ranges

Fig. 1. Property of reinforced barriers and applicability of heterogeneous sensors. (a) Reinforced barriers in homogeneous sensors. (b) Construction of heterogeneous reinforced barriers by different sensing ranges. (c) Heterogeneous reinforced barrier by different communication ranges.

randomly within ROI. Also, we assume each sensor has different sensing ranges $SR = \{sr_1, sr_2, \ldots, sr_n\}$ and also takes different communication ranges $CR = \{cr_1, cr_2, \ldots, cr_n\}$, where $sr_i \neq cr_i$, $s_i \in S$. Note that a sensor s_i only can monitor the area within own sensing range sr_i. Also, it is defined that two sensors, s_i and s_j, can communicate with each other if *euclidian distance* between two sensors, $Euc(s_i, s_j)$, is at most $cr_i + cr_j$ where $s_i, s_j \in S$, $cr_i, cr_j \in CR$, $i \neq j$. It follows that a sensor can report own sensing information within a sensing range to other neighbors within a communication range.

Now, we formally define our proposed type of barriers.

Definition 1 (Heterogenous Reinforced Barrier): Given a set of heterogeneous wireless sensors S randomly deployed over ROI, *heterogenous reinforced barrier* (*HeteRBar*) consists of two paths by heterogenous sensing ranges: one path from BS_1 to BS_2 and another from BS_3 to BS_4 such that every sensor in *HeteRBar* can reach at least one of base stations by different communication ranges.

Definition 2 (Heterogenous Reinforced Barrier-Coverage): heterogenous reinforced barrier coverage is to provide a barrier-coverage that any intrusion by attackers is detected by at least one sensor within *HeteRBar*.

Let us consider Fig. 1(a). Each sensor is depicted as a small circle. It shows a basic formation of reinforced barriers by [5]. Initially, we search for two sets of independent paths: one is between BS_1 and BS_2. Another is between BS_3 and BS_4. Note that *independent path* is equivalent to *node-disjoint path* and each independent path can be considered as one possible barrier. Then, a combination of barrier B_1 and B_3 forms one reinforced barrier. Another is composed of barrier B_2 and B_4. So, the lifetime of reinforced barriers is two since each reinforced barrier is able to be active alternately after one barrier expires. At least one sensor within each reinforced barrier can detect various penetrations of intruders. (i.e. s_1, s_2, s_3 within B_1 and B_3 can detect penetrations of I_1, I_2, I_3. Also, s_4, s_5, s_6 within B_2 and B_4 also detect those attacks, too). Also, Fig. 1(b) describes the construction of *HeteRBar* with different sensing ranges. As shown in Fig. 1(b), B_1 and B_3 consist of one *HeteRBar* which each sensing range is overlapped without any gap between sensors. Another *HeteRBar* is constructed by a combination of B_2 and B_4. Fig. 1(c) shows *HeteRBar*'s another property by different communication ranges, which is that each sensor should have a path to at least one base station for the guaranteed report of intrusion detection. For example, because s_1 is not reachable BS_1 directly, s_1 can reach to BS_4 by a path, $s_1, s_2, s_3, s_4, s_5, s_6, s_7$. Since s_8 has no connection with s_9, s_8 will use the path s_8, s_4, s_5, s_6, s_7 to reach BS_4. Also, s_9 can use a path $s_8, s_{10}, s_{11}, s_{12}$ towards BS_3.

B. Problem Definition

We define our problem formally as follows.

Definition 3 (Lifetime of HeteRBar): A *lifetime* T of *HeteRBar* depends on a set of *HeteRBar* such that for each $p \in T$ and $q \in T$, p and q are disjoint. The *lifetime* T of *HeteRBar* is simply considered as its cardinality, $|T|$.

Definition 4 (MaxHeteRBar Problem): The maximum lifetime heterogenous reinforced barrier-coverage (MaxHeteRbar) problem is to find a maximum number of *HeteRBar*, which is a maximum value of $|T|$.

C. ILP Formulation

The notations used in our ILP formulation as follows.

S: set of sensors.

P_1: set of independent paths between BS_1 and BS_2.

P_2: set of independent paths between BS_3 and BS_4.

n: total number of deployed sensors.

l: total number of independent paths in P_1.

m: total number of independent paths in P_2.

i, j: index of sensor ($1 \leq i, j \leq n$), where $i \neq j$.

a: index of the independent path in P_1 ($1 \leq a \leq l$).

b: index of the independent path in P_2 ($1 \leq b \leq m$).

And the following integer variables are defined in the ILP formulation.

$$X_{a,i} = \begin{cases} 1, & \text{if } i \text{ in } a \text{ reaches at one of base stations} \\ 0, & \text{otherwise.} \end{cases}$$

$$Y_{b,j} = \begin{cases} 1, & \text{if } j \text{ in } b \text{ reaches at one of base stations} \\ 0, & \text{otherwise.} \end{cases}$$

$$Z_{a,b} = \begin{cases} 1, & \text{if } a \text{ and } b \text{ provide reinforced barrier} \\ 0, & \text{otherwise.} \end{cases}$$

Then, our objective function is to maximize the set of *HeteRBar*, which can be expressed as follows.

$$\textbf{Maximize } |T| = \sum_{a=1}^{l}\sum_{b=1}^{m}\sum_{i,j=1}^{n} X_{a,i} \cdot Y_{b,j} \cdot Z_{a,b} \tag{1}$$

Subject to:

$$\sum_{a=1}^{l} X_{a,i} \le 1, \quad (\forall i) \tag{2}$$

$$\sum_{b=1}^{m} Y_{b,j} \le 1, \quad (\forall j) \tag{3}$$

$$Z_{a,b} \le 1, \quad (\forall a, b) \tag{4}$$

An objective function in (1) is to maximize the set of *HeteRBar*, T. So, it maximizes the size of T, $|T|$, satisfying constraints. Constraint (2) represents each sensor i can be used only one time within the independent path set P_1 between BS_1 and BS_2. Similarly, by constraint (3), it is guaranteed that every sensor j can be allowed for one time use within the independent set P_2 between BS_3 and BS_4. Also, constraint (4) forces that the pairing of a in P_1 and b in P_2 has one time match. It follows that if a and b is paired, they can not be paired with other independent paths.

IV. Proposed Approach

To solve the *MaxHeteRBar* problem, we should find maximum number of independent paths from BS_1 to BS_2 and from BS_3 to BS_4, respectively. Then, we consider to construct *HeteRBar* from the found paths.

A. Base Graph

To find the largest number of independent paths, we first create a *base graph* $\mathcal{G} = (V(\mathcal{G}), E(\mathcal{G}))$ as follows.

- For each sensor, find two types of edges (or neighbors): sensing edge and communication edge.
- The sensing edge is added into $E(\mathcal{G})$ if $Euc(s_i, s_j)$ is at most $sr_i + sr_j$, where $s_i, s_j \in S$, $i \neq j$.
- The communication edge is added into $E(\mathcal{G})$ if $Euc(s_i, s_j)$ is at most $cr_i + cr_j$, where $s_i, s_j \in S$, $i \neq j$.
- Assign a capacity of 1 to each sensing edge in $\mathcal{G} = (V(\mathcal{G}), E(\mathcal{G}))$, and perform a maximum flow algorithm, such as Edmonds-Karp algorithm [10], between BS_1 and BS_2. Sensing edges with a flow of 1 will generate independent paths. All other edges will have a flow of 0.

The above steps are also implemented for BS_3 and BS_4.

B. Pre-Combined-Path Approach

First, we propose the *pre-combined-path* approach that returns the maximum collection of *HeteRBar*. The approach initially updates the base graph by considering both sensing and communication edges to find independent paths. The following iterations are performed in *pre-combined-path* approach.

- From current available sensors S', create a base graph $\mathcal{G}$ and update it by assigning a capacity of 1 to each sensing and communication edge in $\mathcal{G} = (V(\mathcal{G}), E(\mathcal{G})$. Both sensing and communication edges with a flow of 1 will generate independent path when a maximum flow algorithm is performed.
- Search for the maximum number of independent paths from BS_1 to BS_2. Also, find the maximum number of independent paths from BS_3 to BS_4.
- A *HeteRBar* is created if we can find a pair of paths: one path from BS_1 to BS_2 and another path from BS_3 to BS_4 such that those paths have at least one sensor in common.
- From the field, remove the sensors in the found pair.

Algorithm 1: *Pre-Combined-Path* Inputs: S, SR, CR, Output: T

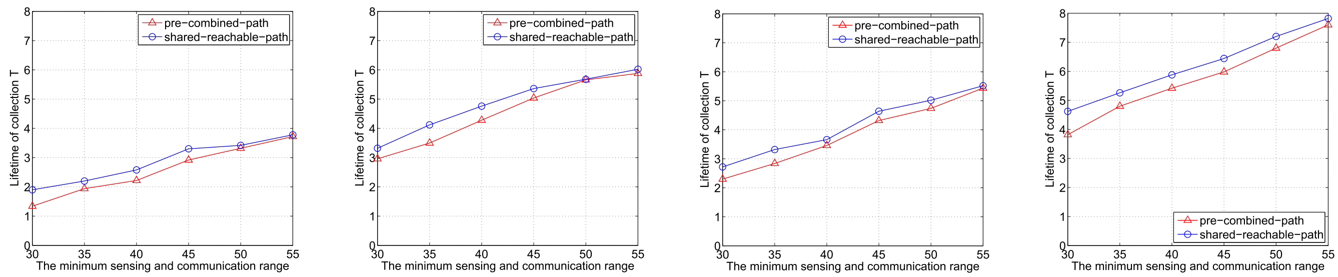
set a collection of *HeteRBar*: $L \leftarrow \emptyset$;
set unselected sensors: $S' \leftarrow S$;
while $S' \neq \emptyset$ **do**
  create a base graph $\mathcal{G}$ using S';
  assign a capacity of 1 to each sensing and communication edge in $\mathcal{G}$;
  let P_1 be the set of independent paths from BS_1 to BS_2;
  let P_2 be the set of independent paths from BS_3 to BS_4;
  find a pair (p_1, p_2) such that $p_1 \in P_1$ and $p_2 \in P_2$, (p_1, p_2) has at least one shared sensor;
  if (p_1, p_2) exists **then**
    $L \leftarrow L \bigcup (p_1, p_2)$;
    $S' \leftarrow S' - \{(\text{sensors in } p_1) \bigcup (\text{sensors in } p_2)\}$;
  else
    break;
  end if
end while
return T

The pseudocode of *pre-combined-path* is described in Algorithm 1 in more detail.

C. Shared-Reachable-Path Approach

Now, we describe the second proposed approach, *shared-reachable-path* using the *base graph*. Iteratively, one *HeteRBar* is found at a time by the following steps.

- Find the maximum number of independent paths from BS_1 to BS_2. Also, search for the maximum number of independent paths from BS_3 to BS_4.
- A *HeteRBar* is created if we can find a pair of paths: one path from BS_1 to BS_2 and another path from BS_3 to BS_4 such that those paths have at least one sensor in common. Also, it requires that every sensor in those paths is reachable to one of base stations. To do so, the following steps are implemented.
  - For reachability verification, check if sensors in the current found pair can reach one of BSs directly using own communication ranges.
  - Also, check if there exists any sensors in the current pair can reach one of verified sensors. If so, those sensors are also verified for reachability.
- If every sensor in the current found pair is verified for reachability, the pair is set to one *HeteRBar*.



(a) $n = 100$ in 500×500 area (b) $n = 150$ in 500×500 area (c) $n = 100$ in 500×400 area (d) $n = 100$ in 500×300 area

Fig. 2. Comparison for lifetime of collection T by two different approaches with different number of sensors and with different area sizes. (a) $n = 100$ in 500×500 area. (b) $n = 150$ in 500×500 area. (c) $n = 100$ in 500×400 area. (d) $n = 100$ in 500×300 area.

Algorithm 2: *Shared-Reachable-Path* Inputs: S, SR, CR, Output: T

set a collection of *HeteRBar*: $L \leftarrow \emptyset$;
set unselected sensors: $S' \leftarrow S$;
while $S' \neq \emptyset$ **do**
  create a base graph $\mathcal{G}$ using S';
  let P_1 be the set of independent paths from BS_1 to BS_2;
  let P_2 be the set of independent paths from BS_3 to BS_4;
  find a pair (p_1, p_2) such that $p_1 \in P_1$ and $p_2 \in P_2$, (p_1, p_2) has at least one shared sensor
  verify every sensor in the pair (p_1, p_2) has a reachable
  if (p_1, p_2) exists **then**
    $L \leftarrow L \bigcup (p_1, p_2)$;
    $S' \leftarrow S' - \{(\text{sensors in } p_1) \bigcup (\text{sensors in } p_2)\}$;
  else
    break;
  end if
end while
return L

- From the field, remove the sensors in the found pair.

The above steps are iterated until we can not obtain any additional pair of paths. The pseudocode of *shared-reachable-path* is presented in Algorithm 2 in more detail.

V. Experimental Evaluation

In section, we evaluate the performance of the proposed two approaches: *pre-combined-path* and *shared-reachable-path*. For the used simulation settings, we have used ad-hoc simulator. The simulation codes based on C^{++} for the proposed approaches were implemented by the server which is equipped with Dual Core AMD Opteron Processor 285 with cache size 1024 KB and CPU op-mode with 32 bit and 64-bit. Given those environments, the simulations were performed in square-shaped areas such as $500 \times 500\ m^2$, $500 \times 400\ m^2$, $500 \times 300\ m^2$. Also, n number of sensors with $n = 100$ and 150 are deployed randomly in those areas. We considered that the sensing ranges SR and the communication ranges CR are between 30 and 70, respectively. Note that each numerical result represents the average value of 100 different graph sets.

As the first group of experiments, with the setting 70 as the maximum sensing and communication ranges, we compared two approaches by different minimum sensing and communication ranges in $500 \times 500\ m^2$ area. Fig. 2(a) and 2(b) shows the results with $n = 100$ and $n = 150$. We have checked that as the difference between minimum range and maximum range for sensing and communication increases, *shared-reachable-path* shows the better performance than *pre-combined-path* for both cases $n = 100$ and 150. For another group of simulations, we implemented two approaches with various sizes of areas such as $500 \times 400\ m^2$ and $500 \times 300\ m^2$. As it can be seen in Fig. 2(c) and 2(d), we have verified that as the difference between minimum range and maximum range is bigger, *shared-reachable-path* returns a bigger value for the lifetime of T than *pre-combined-path*.

VI. Conclusion

In this paper, we proposed *HeteRBar* which each sensor has different sensing ranges and communication ranges. Also, we formally defined a problem whose goal is to maximize a lifetime of *HeteRBar*. To solve the problem, we created a base graph of heterogeneous sensors and then proposed two approaches using the base graph. Then, the performance of the proposed schemes is evaluated through various scenarios.

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