

Automatic Barrier Coverage Formation with Mobile Sensor Networks

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Abstract—In sensor networks many efforts have been made on barrier coverage. Most of them rely on the assumption that sensors are randomly or manually deployed around the region of interest. It is obvious that the random deployment wastes many redundant sensors without contribution on the barrier formation. Moreover, in most real scenarios, it is difficult to deploy sensors manually due to the region usually in large scale or in danger. Hence, this paper studies the problem that using mobile sensors to form barrier surrounding the region automatically. The fundamental objective is to take full advantage of the limited number of mobile sensors to form the barrier coverage with the highest detection capability. The challenge is that the sensors only have local information. A fully distributed algorithm based on virtual force and convex analysis is developed for the objective to relocate the sensors from the original positions to uniformly distribute on the convex hull of the region. Simulation results verify the validity of our proposed cooperative scheme.

Key Words—Barrier coverage formation, wireless sensor networks, mobile sensor, virtual force

I. INTRODUCTION

Barrier coverage is an important problem in wireless sensor networks (WSNs) [1], which guarantees to detect any intruder attempting to cross the barrier of sensor networks or penetrating the protected region. A wide range of practical scenarios require barrier coverage such as locating minefield in military, detecting radiation spills around nuclear industries and monitoring the spread of forest fire. Formation phase in barrier coverage is an indispensable process since newly deployed sensors lack a reliable infrastructure for communication and detection. This phase requires finding several chains of sensors enclosing the region with the sensing areas of adjacent sensors overlapping with each other [2].

A variety of barrier coverage involving formation solutions have been proposed in the literature. Kumar *et al.* [2] developed a centralized algorithm to determine whether a region is weakly k -barrier covered in a randomly deployed sensor network. Chen *et al.* [3] later designed a localized algorithm that guarantees the detection of intruders in a certain length belt region. Balister *et al.* [4] estimated the reliable density that achieves barrier coverage in a finite region. In [5], Liu *et al.* devised efficient algorithms to construct strong sensor barriers. Saipulla *et al.* [6] studied the barrier coverage of line-based deployment.

In state-of-the-art studies, most works assume that the sensors without motion ability are randomly or manually deployed around the region of interest before barrier formation. However, the random deployment hypothesis requires much more re-

dundant sensors than the number of sensors forming barrier chains. Arbitrary deployment could avoid this waste of resources. Nevertheless, in realistic case, the region of interest is usually large in scale and the task is danger and dull. It is impossible to deploy all sensors manually. Therefore, this paper introduces a solution that mobile sensors relocate their positions and self-organize barrier coverage for the region.

In practice, the number of sensors is generally determined before deployment. The basic objective is to take full advantage of the limited number of mobile sensors to achieve the optimal distribution, which results in the barrier coverage with the maximal number of k -barrier [2]. However, sensors have no prior knowledge of their deployed positions or the global information of the region. Hence, they can rely only on the sensed and communicated local information to move. This poses a great challenge on forming barrier coverage.

The barrier coverage formation problem is studied on a 2D plane. The region of interest has a continuous and stationary boundary. The source positions of the sensors are considered following any distribution on the plane. The destinations according to optimal distribution pattern are derived by convex analysis. Several additional objectives are discussed for alternative including the dynamic region and the group arbitrary release of sensors' source positions. A fully distributed algorithm based on virtual force is devised, which cooperatively controls the sensors to move approaching the optimal distribution pattern. Performance evaluation verifies the validity of the algorithm and analyzes properties such as formation duration and energy cost.

In summary, the contributions of this paper are as follows:

- To our best knowledge, this is the first work that motivates the problem of automatic barrier coverage formation using mobile sensor networks.
- Theoretical optimal distribution of sensors for maximal k -barrier coverage is derived to guide the movement.
- A cooperative control algorithm is developed for sensors to automatically form the barrier coverage. This algorithm is valid in both static and dynamic region.

The rest of the paper is organized as follows: Section 2 formulates the barrier coverage formation problem and analyzes the optimal distribution pattern. Section 3 introduces the cooperative control algorithm based on virtual force. Section 4 presents and analyzes the simulation results. In Section 5, we give conclusion and future work.

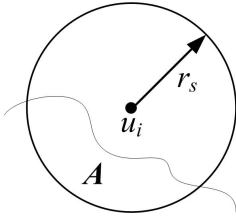


Fig. 1. Disk model of a sensor u_i whose sensing range is r_s covering a part of region A .

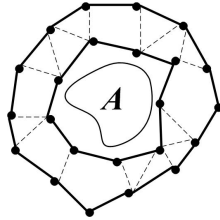


Fig. 2. Coverage graph of strong k -barrier coverage surrounding region A , where $k = 2$.

II. BARRIER COVERAGE FORMATION ANALYSIS

A. Model

The region of interest A is an area enclosing some types of substance on a 2D plane. Assume that the region is static and has a continuous boundary.

A mobile sensor u_i moves with a velocity v on the plane. The sensing area is assumed to be the widely adopted disk model. In this disk with a radius r_s , a sensor has the ability to distinguish out whatever substance it is trying to besiege as shown in Fig. 1. A sensor knows its location information (x_i, y_i) with equipping affiliated devices such as GPS. The communication range between sensors is r_c , where assume $r_c > 2r_s$. Generally, the number of sensors n is given before deployment.

Barrier coverage in [2] is described by a coverage graph $G(n) = (V, E)$. The set V consists of a vertex corresponding to each sensor. An edge exists between two vertexes if their distance is less than $2r_s$. Strong barrier coverage [5] is presented as a closed chain, which is composed of the edges enclosing the region. Since the sensors have the capability of movement, only strong barrier coverage formation is considered in this study. The strong k -barrier coverage is referred that there are number k of vertex disjointed chains in $G(n)$. Fig. 2 introduces a $k = 2$ strong barrier coverage graph. The detection capability is usually measured by the number k .

B. Fundamental Problem Statement

One advantage of barrier coverage is that it saves huge number of sensors than full coverage when protecting a region from intruders. Most studies [2][3][4][5][6] assume that sensors without movement ability are randomly deployed around the region. There are also many redundant sensors wasted during the barrier coverage formation. If fewer sensors can form the same strong k -barrier coverage, it will be more beneficial in cost.

Obviously, manual deployment can take full advantage of n sensors to set approximate optimal barrier coverage. However, since the region of interest is usually large in scale and the arbitrary deployment task may be dangerous, it is difficult to deploy sensors manually. Therefore, the mobile sensor is considered as one of the best candidates to solve this problem.

The automatic barrier coverage formation problem is defined to be the problem that *mobile sensors automatically move from their source positions to form the strong k -barrier coverage for the region of interest.*

The objective of solving the problem is to maximize k with given n . Then, all sensors form the maximal k -barriers without

incurring waste. That is to say, given the demand of barrier coverage, the number of sensors will be minimized.

The main difficulty to solve this problem lies in that sensors have only local information by communication and sensing. Then, how the sensors know their destination and what paths they move along without global information? The destination is analyzed in Subsection C, additional requirements are considered in Subsection D and the path is designed in Section III.

C. Optimal Distribution Pattern

The optimal destination of n vertexes is defined to follow the distribution of consisting maximum k vertex disjointed chains in coverage graph $G(n)$.

Additionally, $f_c(A)$ is a function of the length of the convex hull of the region A . The method of obtaining $f_c(A)$ can be found in [7]. Thus, we have:

Theorem 2.1 A sufficient condition of achieving maximum k is that n sensors are uniformly distributed on the convex hull of the region A . The maximum value of k is

$$k = \frac{2nr_s}{f_c(A)}. \quad (1)$$

Proof: We prove this theorem by introducing the following three lemmas.

Lemma 2.1 The shortest perimeter enclosing the region A is its convex hull.

According to convex analysis [7], the smallest area and the shortest perimeter polygon containing a 2D region is its convex hull. Hence, the shortest perimeter equals to $f_c(A)$. In other words, the least length of one barrier chain is $f_c(A)$.

Lemma 2.2 The longest length consisted by vertexes is $2nr_s$.

Due to the edge definition in coverage graph that an edge exists when $d(u_i, u_j) \leq 2r_s$, the longest distance between any two connectable vertexes is $2r_s$. Connecting n vertexes in series, then, the longest length of all these vertexes is $2nr_s$.

Wind the series of vertexes to the convex hull of region A . Combining with Lemma 2.1 and 2.2, the theoretical maximum value of the number of chains k can be computed as

$$k = \frac{2nr_s}{f_c(A)}.$$

Lemma 2.3 It is a sufficient condition for achieving optimal k that n vertexes are uniformly distributed on the shortest barrier perimeter of the region A .

If all vertexes are distributed on the shortest perimeter, several vertex disjointed chains will overlap completely. In this case, any point on the perimeter is covered by a few sensors. The least covered number is treated to the k . It can be described that when an intruder crosses the barrier from any path, there are at least k sensors detecting it. This concept is transformed from the strong k -barrier coverage definition in [2] for this case.

In Lemma 2.3, n vertexes are uniformly distributed. Hence, k is equivalent for every point on the perimeter. We have the distance between any pair of adjacent neighbors

$$\Delta = \frac{f_c(A)}{n}. \quad (2)$$

And any point on the perimeter is covered by at least

$$k = \frac{2r_s}{\Delta}. \quad (3)$$

Combining Eqn. 2 and Eqn. 3, we have

$$k = \frac{2r_s}{\Delta} = \frac{2nr_s}{f_c(A)}. \quad (4)$$

It is the same result as Eqn. 1, which proves the condition is sufficient. Then the result of Theorem 2.1 follows. ■

D. Alternative Objectives

Generally, the basic objective of $\max(k)$ satisfies most practical scenario. However, there are still several alternative objectives remained in barrier coverage formation problem.

First, consider another type of region: dynamic. A dynamic region has a time-varying boundary. Thus, the area or the shape of the region changes over time. An oil leak is such an instance.

Second, consider a more practical distribution of sensors' source positions: group release. To put all sensors manually at one or just a few points on the boundary of the region corresponds to reality. For example, put all mobile sensors in front of the gate of a nuclear factory. And then, the sensors automatically move to form barrier coverage surrounding the factory.

These alternative objectives can appear either in single form or in any combination form in barrier coverage formation.

III. ALGORITHM

A. Chain Reaction Algorithm

The source position of sensor is assumed to follow random distribution in the basic problem, while the optimal distribution of destination is derived. Then in this section we develop a cooperative algorithm for the sensors moving automatically from their source to destination with only local information.

To solve this problem, we propose a chain reaction algorithm with two steps: boundary seeking and barrier forming.

Step 1: Boundary seeking. Since sensors are randomly distributed on the plane and have only local information, some of them do not know the location of region A . In order to form the barrier, sensors should know the boundary of region. All source positions can be classified into the following three cases.

Case 1: outside the boundary. A sensor u_i is defined to be outside the boundary when $d(u_i, A) > r_s$. The sensing area of u_i has no overlap with the region A . In this case, in order to find the boundary, a sensor can move along a spiral as shown in Fig. 3(a). This spiral path is applied to boundary detection in [8]. The advantage of this path is that it seeks the boundary with equal probability on all directions and will not miss the region.

Case 2: on the boundary. $B(A)$ is denoted as a function to get the boundary of region A . A sensor u_i is defined to be on the boundary when $d(u_i, B(A)) \leq r_s$. The sensing area of u_i has partial overlap with the region. In this case, a sensor can select the shortest path to the boundary as shown in Fig. 3(b).

Case 3: inside the boundary. A sensor u_i is defined to be inside the boundary when $d(u_i, B(A)) > r_s$ and the sensing area of sensor u_i is included by region A . A sensor in this case can move in a straight line after randomly selecting a direction to the boundary as shown in Fig. 3(c).

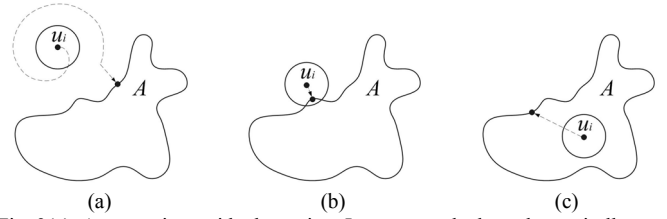


Fig. 3(a). A sensor is outside the region. It moves to the boundary spirally. Fig. 3(b). A sensor is on the boundary. It moves to the boundary directly. Fig. 3(c). A sensor is inside the region. It moves to the boundary straightly.

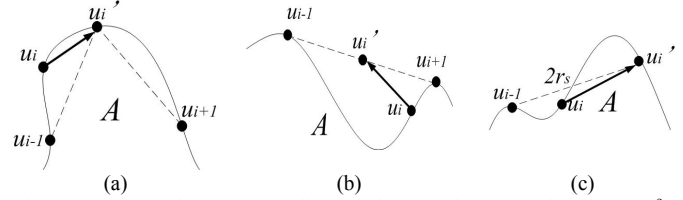


Fig. 4(a). Sensor u_i has two immediate neighbors and its internal angle $< 180^\circ$. It moves to a position on the boundary where $d(u_i, u_{i-1}) = d(u_i, u_{i+1})$.

Fig. 4(b). Sensor u_i has two immediate neighbors and its internal angle $\geq 180^\circ$. It moves to a position that is the middle of u_{i-1} and u_{i+1} .

Fig. 4(c). Sensor u_i has only one immediate neighbor. It moves away from its neighbor u_{i-1} at $2r_s$ distance and along the boundary of region A .

Step 2: Barrier forming. After finding the boundary, sensors cooperatively move to form the $\max(k)$ barrier coverage. A sensor has two directions along the boundary: clockwise and counterclockwise. The nearest neighbor of either direction is denoted as an immediate neighbor. The cooperation is worked through location information transmission among immediate neighbors, which is easy to realize with high energy efficiency and shorter delay. Since each sensor seeks the boundary itself, its neighbor situation is uncertain. There are also three cases of immediate neighbors on the boundary.

Case 1: two immediate neighbors. When a sensor u_i has two immediate neighbors u_{i-1} and u_{i+1} on each side, virtual force [9] is produced from these two neighbors. The magnitude of force depends on the distance $d(u_i, u_{i-1})$ and $d(u_i, u_{i+1})$. In order to balance the two forces, a sensor move along the boundary to the position where $d(u_i, u_{i-1}) = d(u_i, u_{i+1})$. Moreover, a sensor with its two immediate neighbors can form two angles. The internal angle is defined as the angle facing the region. A sensor should keep the internal angle no more than 180° . In Fig. 4(a), the internal angle of u_i is sharp. In order to balance the force, the destination is u_i' . In Fig. 4(b), the part of the boundary is concave, so the internal angle of u_i is more than 180° . In order to balance and keep the angle limitation, the destination is the middle position between u_{i-1} and u_{i+1} .

Case 2: one immediate neighbor. When a sensor u_i has only one immediate neighbor u_{i+1} on one side, virtual force is produced and the magnitude is denoted as $d(u_i, u_{i+1})$. Due to this force, sensor u_i walks towards the direction without the immediate neighbor until $d(u_i, u_{i+1}) = 2r_s$.

Case 3: no neighbor. When a sensor has no neighbor in its communication range, there is no virtual force for it to move.

Due to the virtual force in these three cases, sensors can move cooperatively. All sensors move until they are uniformly distributed on the convex hull of the region while all virtual force is balanced. Obviously, the barrier forming is a chain reaction process. Hence, it needs time to converge to steady

state.

The metrics to measure the quality of automatic barrier formation algorithm include the travel distance of sensors and the time of formation duration.

The detailed algorithm is shown as follows:

<p>Chain Reaction Algorithm (Executed on sensor u_i)</p> <p>Input: the sensing range r_s,</p> <p>while True do</p> <p> Sense the substance of region A with in r_s disk;</p> <p> switch (Location)</p> <p> case outside boundary: spiral_moving(); break;</p> <p> case on boundary: direct_moving(); break;</p> <p> case inside boundary: straight_moving(); break;</p> <p> // step 1 finish</p> <p> Get current location information p_c;</p> <p> Detect the immediate neighbors u_{i+1} and u_{i-1};</p> <p> Exchange position information with u_{i+1} and u_{i-1};</p> <p> // p is the next position u_i will to move, θ is the internal angle</p> <p> switch(Num of immediate neighbors)</p> <p> case 2:</p> <p> if($\theta \geq 180$) $p \leftarrow$ middle point of u_{i+1} and u_{i-1};</p> <p> else $p \leftarrow q$ where $d(p_{u_{i+1}}, q) = d(p_{u_{i-1}}, q)$ and $d(q, A) = 0$;</p> <p> break;</p> <p> case 1: $p \leftarrow q$ where $d(p_{u_{i+1}}, q) = 2r_s$ and $d(q, A) = 0$;</p> <p> break;</p> <p> default: $p \leftarrow p_c$;</p> <p> break;</p> <p> Move to p along the boundary of the region;</p> <p> // step 2 finish</p> <p>end while</p>
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B. Algorithm Extension

For the dynamic region, most parts of chain reaction algorithm can be hold. Only one function demands to be complement, which a sensor should keep seeking the time-varying boundary instead of relocating once. The boundary seeking step is executing continuously while forming the convex hull with other sensors. This algorithm can also be used in the barrier reformation situation when some sensors are failure.

For different distribution of sensors' source positions, no matter following the Gauss, Poisson or any other distribution, the chain reaction algorithm is available without any modification. For instance, in the group release case, the source position can be treated that all sensors are deployed at the same location, which is only a special case for distribution. Hence, the basic algorithm is sufficient.

IV. PERFORMANCE EVALUATION

A. Simulation Settings

In the basic requirement (BR) simulation, the region of interest is set red as Fig. 5(a) and the other part of the plane is set white. The red region has a continuous boundary and its shape is fixed. The size of the plane is set to be 800*600m. There are 50 mobile sensors deployed on this plane, whose source positions are randomly selected. We assume that a sensor can detect and distinguish red or white within its sensing range $r_s = 25$ m.

Sensors can transmit information in their communication ranges $r_c = 60$ m. The velocity of a sensor is at most 10m/s.

In the dynamic region (DR) case, the red region transforms from a circle to the shape as shown in Fig. 6(d) in 500s.

In the group release (GR) scenario, 50 sensors are set in the same location (301, 109) for their source positions as fig. 7(a).

We implement the chain reaction algorithm and extension algorithms in these simulation cases. Fig. 5, 6 and 7 show the different instants obtained by the algorithms.

B. Performance Analysis

The results of Fig. 5, 6 and 7 verify the validity and generality of our algorithms in solving automatic barrier coverage formation problem. Finally, they all form barrier coverage with $k = 2$.

In Fig. 8, the accumulated travel distance over time is shown. As we know, a short travel distance can be treated as lower energy consumption on movement. The total travel distance in three cases is 61367m, 48089m and 43743m at 500s respectively. Since sensors have no global information, the redundant travel distance is inevitable such as zigzag path in seeking boundary. However, in the simulation, we find that there is little turning back for sensors with our algorithms, which means only little energy wasted on movement. Among the three curves in Fig. 8, we find that BR has the most accumulated travel distance over time compared to DR and GR. The reason is that the zigzag seeking path costs much travel distance. In DR, the initial region is so large that there are fewer sensors outside the region than those in BR. And the sensors in GR do not require the boundary seeking step.

Moreover, we study the convergence duration. The convergence condition for a sensor is that the distance between its current position and next position is less than a threshold of 0.1m. When all sensors achieve the convergence condition, the barrier coverage formation process is completed. With this condition, all the three simulations can converge. From Fig. 9, we obtain the durations are 855s, 685s and 510s, respectively. We find that BR is the slowest process to converge compared to DR and GR. The reason is that the sensors in BR cost the most time to seek the boundary while the least in DR.

V. CONCLUSION

The problem of automatic barrier coverage formation by mobile sensors is addressed in this paper. The chain reaction algorithm is proposed on sensors to move automatically and cooperatively from their source positions to form maximal k strong barrier coverage. This algorithm can be widely applied to different initial states such as random or arbitrary deployment. It could also be extended to protect the dynamic region.

Since the barrier coverage formation problem is newly raised, there exist several open questions for further study. One of our future works is that the movement ability of mobile sensors is constrained by the terrain situation. For example, the obstacles exist on the plane. Second, energy problem is critical for mobile sensors. To study the optimal path of minimal travel distance for all sensors is another future work.

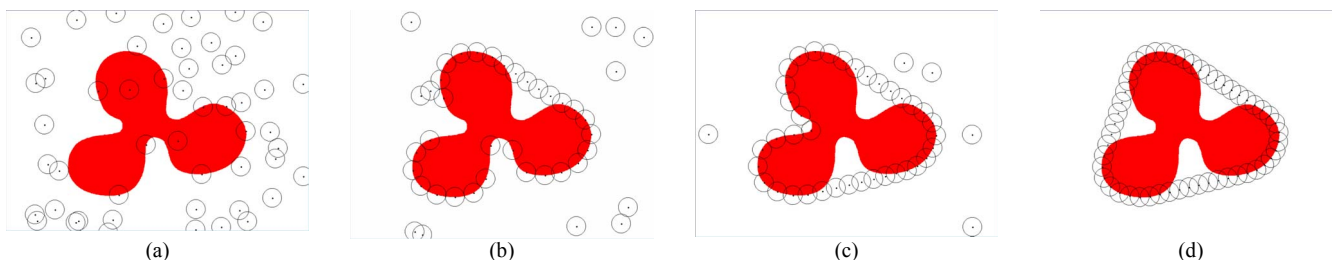


Fig. 5. Four snapshots of the automatic barrier coverage formation process by chain reaction algorithm on mobile sensors in the basic requirement (BR) simulation. The region is fixed. The source positions of sensors are randomly selected.

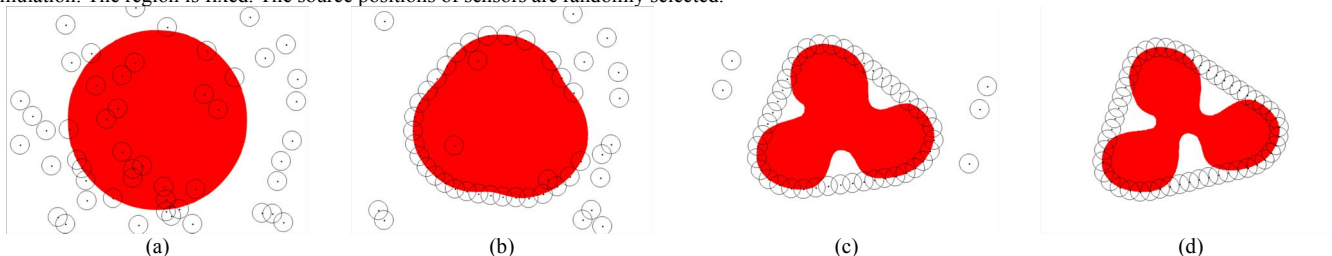


Fig. 6. Four snapshots of the automatic barrier coverage formation process by extension chain reaction algorithm on mobile sensors in the dynamic region (DR) simulation. The region is time-varying. The source positions of sensors are randomly selected.

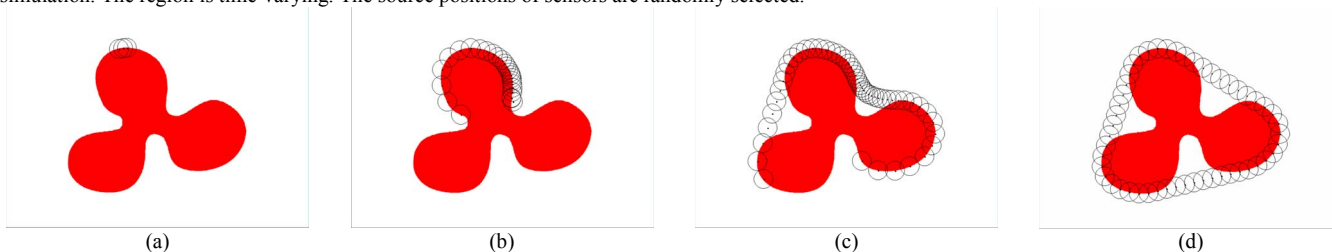


Fig. 7. Four snapshots of the automatic barrier coverage formation process by chain reaction algorithm on mobile sensors in the group release (GR) simulation. The region is fixed. All sensors are released in the same position at the beginning.

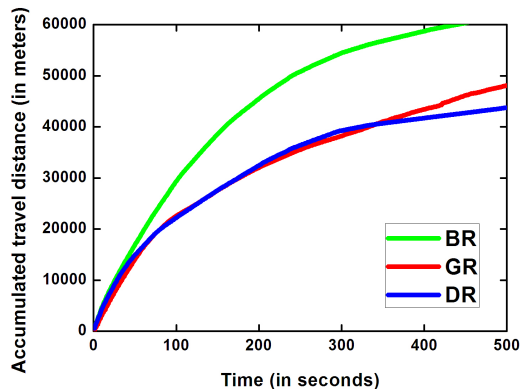


Fig. 8. The accumulated travelled distance of all sensors over time.

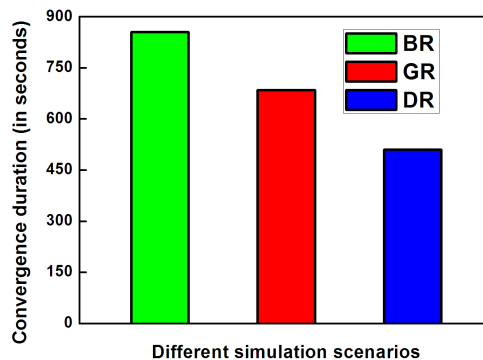


Fig. 9. The convergence duration of chain reaction algorithm.

VI. ACKNOWLEDGEMENT

This research was partially supported by NSF of China under grant No. 60773091, 973 Program of China under grant No. 2006CB303000, Key Program of National MIIT under Grants no. 2009ZX03006-001 and 2009ZX03006-004.

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