Barrier Coverage with Sensors of Limited Mobility

Anwar Saipulla † Benyuan Liu † Guoliang Xing * Xinwen Fu † Jie Wang †

† Department of Computer Science
University of Massachusetts Lowell
Lowell, MA 01854, USA
{asaipull, bliu, xinwenfu, wang}@cs.uml.edu

* Department of Computer Science and Engineering
Michigan State University
East Lansing, MI 48824
glxing@msu.edu

ABSTRACT

Barrier coverage is a critical issue in wireless sensor networks for various battlefield and homeland security applications. The goal is to effectively detect intruders that attempt to penetrate the region of interest. A sensor barrier is formed by a connected sensor cluster across the entire deployed region, acting as a "trip wire" to detect any crossing intruders. In this paper we study how to efficiently improve barrier coverage using mobile sensors with limited mobility. After the initial deployment, mobile sensors can move to desired locations and connect with other sensors in order to create new barriers. However, simply moving sensors to form a large local cluster does not necessarily yield a global barrier. This global nature of barrier coverage makes it a challenging task to devise effective sensor mobility schemes. Moreover, a good sensor mobility scheme should efficiently improve barrier coverage under the constraints of available mobile sensors and their moving range. We first explore the fundamental limits of sensor mobility on barrier coverage and present a sensor mobility scheme that constructs the maximum number of barriers with minimum sensor moving distance. We then present an efficient algorithm to compute the existence of barrier coverage with sensors of limited mobility, and examine the effects of the number of mobile sensors and their moving ranges on the barrier coverage improvement. Both the analytical results and performance of the algorithms are evaluated via extensive simulations.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Network topology*

General Terms

Algorithms, Design, Theory, Performance

MobiHoc'10, September 20–24, 2010, Chicago, Illinois, USA.

Keywords

Wireless sensor networks, coverage, mobility, analysis, algorithm

1. INTRODUCTION

Wireless sensor networks have become a powerful tool for many military and homeland security related applications, including battlefield perimeter surveillance, critical infrastructure (e.g., ports, nuclear power plants) protection, and country border control, to name a few. In these applications, sensors are deployed to monitor the region of interest and detect intruders. The barrier coverage of a sensor network characterizes its capability to detect intruders that attempt to cross the deployed region into protected areas. Due to its unique requirement, the barrier coverage of a wireless sensor network exhibits different characteristics and calls for different design considerations than other coverage measures such as area coverage and point coverage.

Recently, there has been increasing interest in deploying mobile sensor networks, which can be extremely valuable in hostile environments such as battlefields and hazardous areas. Numerous mobile sensor platforms have been developed, including Packbot [1], Robomote [2], and Khepera [3], etc. As technologies advance, these mobile sensor platforms will become increasingly available and may be deployed on a large scale in practical applications in the future.

Most of the previous studies on the barrier coverage of wireless sensor networks consider constructing barriers with stationary sensors [4, 5, 6, 7, 8, 9]. While there has been much effort investigating how to move sensors to improve area coverage of a wireless sensor network [10, 11, 12, 13], the impact of sensor mobility on barrier coverage has not been adequately explored.

In wireless sensor networks, a barrier is formed by a chain of overlapping sensors that spans the entire region of interest. While placing sensors side by side regularly along a straight line across the region provides the most efficient barrier coverage, it is infeasible to achieve in many applications scenarios. When deploying sensors to monitor hostile or hard-to-reach areas, e.g., battlefields or remote country borders with complex terrains, we may have to rely on other deployment methods such as dispersing sensors from an aircraft or artillery ordinance, resulting in a random sensor distribution.

In [6], it has been shown that barrier coverage is difficult to achieve when sensors are randomly deployed. This is because a large fraction of sensors will not contribute to barrier coverage. In a mobile sensor network, after the initial deployment, mobile sensors can move to desired locations and connect with other un-utilized sensors to form new barriers, as illustrated in Figure 1. Therefore, it is important to effectively exploit sensor mobility so as to improve barrier coverage. Otherwise, a sensor network deployment may not achieve its coverage goal and the sensors will be wasted.

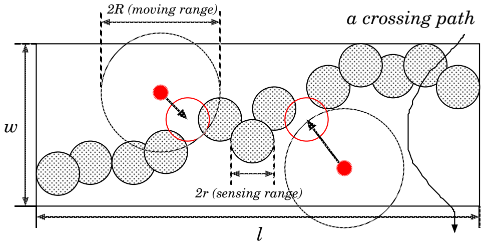

Figure 1: Mobile sensors relocate themselves to contribute to barrier coverage of the network. Sensors are deployed in rectangular region of $\ell \times w$. Sensors' sensing range is r, and mobile sensors' maximum moving range is R.

While the potential improvement is promising, it is challenging to compute a desired location for each mobile sensor to move to, as well as to explore the performance potentials of sensor mobility, due to the non-local nature of the barrier coverage. For example, in Figure 1, a barrier will be formed only when both mobile nodes are relocated to the desired locations as illustrated. Moreover, another challenge of constructing barriers with mobile sensors is that existing mobile sensor platforms are often powered by small batteries which significantly limit the range of their movement. For instance, the on-board batteries of Robomote nodes only last for about 20 minutes in full motion. Given a typical speed of 15 cm/sec, the range of movement is only about 180 meters [2].

Given a network scenario (initial sensor deployment, number of mobile sensors and their moving ranges), it is desirable to form the maximum number of disjoint barriers so as to provides effective and robust defense against intruders. The final barrier coverage is dictated by the sensor mobility scheme that determines the location that each mobile sensor should move to. A desirable sensor mobility scheme should take advantage of the existing network topology and efficiently improve barrier coverage under the limited mobility constraint.

Moving sensors to join a large local cluster may not create new barriers, as the cluster may not continue to cross the whole region. The creation of a new barrier often require multiple sensors to be relocated to certain locations respectively. However, a sensor cannot move to an arbitrary location due to its limited moving range. Moreover, while a mobile sensor may move to any location within its moving range, it can only contribute to at most one disjoint barrier.

We are interested in the following research problems: Where should each mobile sensor move to maximize the number of barriers that can be formed? How does the improvement depend on the number of available mobile sensors and their moving range? What are the fundamental limits of the barrier coverage using mobile sensors and what is the corresponding mobility requirement? Answers to these questions provide important insights into the design and performance of wireless sensor networks for barrier coverage.

The main contributions of this paper are listed as follows:

- We first explore the fundamental limits of the barrier coverage under sensor mobility. When a total number of m mobile sensors are deployed in a rectangular area of dimension $\ell \times w$, if all sensors have a sensing range of r, we show that a maximum number of $\lfloor \frac{2mr}{\ell} \rfloor$ barriers can be formed, and the minimum of the maximum (minimax) moving distance among all sensors is $\Theta(\sqrt{\ell r} + w)$ w.h.p. We further present an efficient sensor mobility scheme that achieves the maximum barrier coverage and minimizes the maximum sensor moving distance.
- We show that sensor mobility can effectively lower the percolation threshold of the network, and thus improve the barrier coverage probability. We further devise an algorithm that computes the existence of barrier coverage under the limited sensor mobility constraint, and constructs a barrier should it exist. Through extensive simulations we examine the impact of sensor mobility on barrier coverage. Our results show that the fraction of mobile sensors or the moving range of mobile sensors has to reach a certain level before the barrier coverage starts to improve. After this, the improvement rises rapidly and levels off after all possible new barriers are formed.

The rest of the paper is organized as follows. Section 2 reviews the related work on barrier coverage of sensor networks. Section 3 describes the network model used in this study. Section 4 explores the fundamental limits of barrier coverage under sensor mobility. We present an efficient sensor mobility scheme that achieves the maximum barrier coverage and minimizes the maximum sensor moving distance. In Section 5, we present an algorithm to compute whether a network with mobile sensors is barrier coverable, and examine the impact of sensor mobility on barrier coverage. Finally, we conclude the paper in Section 6.

2. RELATED WORK

The notion of barrier coverage was first introduced in the context of robotic sensors [14]. For wireless sensor networks, [15, 16] studied the path coverage and exposure problems, and presented efficient algorithms to find the maximum breach path and minimum exposure path. Later, several distributed algorithms were devised for the path coverage problems [17, 18]. In [19], the authors investigated the detection of intruders traversing the region using collaborative detection schemes among sensors.

In [4], Liu and Towsley studied the barrier coverage problem on two-dimensional plane and two-dimensional strip sensor networks using percolation theory. The barrier coverage of a two-dimensional plane network is related to the existence of a giant sensor cluster that percolates the network. Recently, Liu, Dousse, Wang, and Saipulla derived the critical conditions for the existence of barrier coverage and devised efficient algorithms to construct sensor barriers [6]. In [20, 21], the percolation and barrier coverage of three-dimensional sensor networks are studied.

Kumar, Lai, and Arora [5] introduced the notion of weak coverage and derived the critical conditions for the existence of weak barrier coverage in a randomly deployed sensor network. Later, Chen, Kumar, and Lai [22] devised a localized algorithm that guarantees the detection of intruders whose trajectory is confined to a slice of the belt region of deployment. In [7], Chen, Lai, and Xuan studied how to measure and ensure the quality of barrier coverage in wireless sensor networks. In [9, 23], Yang and Qiao studied the effects of sensor collaboration and multi-round deployment on barrier coverage.

Most of the early work assumes that the sensor locations follow a Poisson point process where sensors are distributed in a large area uniformly at random. Saipulla et al. first considered an application scenario where sensors are dropped along certain lines with random offsets [24], and established analytical results for the barrier coverage probability in [8].

The impact of sensor mobility on network coverage has been investigated in several studies. Amaldi et al. proposed an optimization framework for selecting sensor positions to detect mobile targets traversing a given area [25]. Chellappan et al studied the issue of relocating mobile sensor with limited moving range to minimize the variance in number of sensors among the regions and simultaneously minimize the sensor movements [13]. In [26], Shen et al proposed a virtual force based heuristic algorithm to relocate mobile sensors to form barriers. Using a game theoretic approach, sensor movement strategies are studied to defend against intrusions in wireless sensor networks [27, 28]. In [29, 30], two algorithms are proposed to schedule the movement of mobile sensors that collaborate via data fusion to achieve the desirable spatiotemporal sensing performance.

Compared to early studies on barrier coverage [4, 5, 6, 7, 9, 24, 8], our paper studies the barrier coverage problem with mobile sensors. Compared to other papers on mobile coverage problems [13, 25, 26, 28], our paper is the first to consider barrier coverage problem with mobility constrained sensors and we also established a minimum required moving range to efficiently construct barriers with mobile sensors.

3. NETWORK MODEL

Two classes of sensor location distribution models have been considered in the previous studies: the uniform distribution model where sensors are deployed in a region uniformly at random, and the line-based model where sensors are deployed along certain lines [8]. Both models are valid and applicable for different application scenarios. For example, when sensors are dropped by an aircraft along its flying route, the sensor distribution follows the line-based model. If sensors are launched from artillery ordinance to an area uniformly at random, it may be approximated by the uniform distribution model. In this paper we focus on the impact of sensor mobility on the barrier coverage under the uniform random model.

We adopt the commonly used binary disk sensing model. All the sensors have a common sensing radius of r. A sensor can detect an intruder if and only if the intruder is within distance r from the sensor. In practice, sensing areas are never perfect disks. However, the disk model can provide lower and upper bounds for realistic irregular sensing areas [31].

In the initial deployment, a combination of n stationary and m mobile sensors are distributed uniformly at random in a large two-dimensional rectangle area of size $\ell \times w$. Due to the application characteristics of barrier coverage, the deployment region is often a thin strip area, for example, boundaries of a battlefield and perimeters of a nuclear plant. The length of the rectangle is usually significantly larger than its width, i.e., $\ell \gg w$. In the asymptotic case, $\ell(n), w(n) \to \infty$ as $n, m \to \infty$, the initial sensor locations follow a Poisson point process. The densities of the stationary and mobile sensors are $\frac{n}{\ell(n)w(n)}$ and $\frac{m}{\ell(n)w(n)}$, respectively.

After the initial deployment, mobile sensors can relocate themselves. Due to power constraint, we assume each mobile sensor has a maximum moving range of R. As shown in Figure 1, a mobile sensor, initially located at (x_0, y_0) can move to any location within a circle of radius R, i.e., any point (x, y) with $(x - x_0)^2 + (y - y_0)^2 \le R^2$.

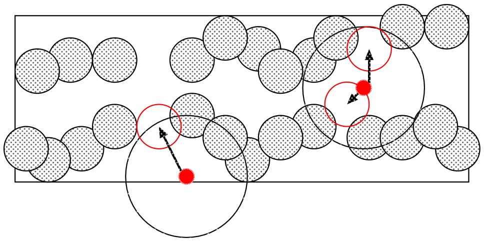

Figure 2: Example for non-locality of mobile barrier coverage problem.

In a wireless sensor network, a *crossing path* is a continuous curve that connects one side of the deployed region to the opposite side. For a two-dimensional rectangle, we assume that the intruders attempt to cross the width of the rectangle area, as depicted in Figure 1. A barrier is a chain of overlapping sensors across the entire region. Clearly, such a barrier will intersect any crossing paths and thus is guaranteed to detect any crossing intruders.

A wireless sensor network is barrier covered if there exists at least one barrier. The strength of the barrier coverage of a sensor network can be measured by the number of disjoint barriers that an intruder crosses over when traversing through the network.

A challenge to using sensor mobility to improve barrier coverage is the *non-locality* nature of the problem. As shown in Figure 2, based on location information of nearby sensors, the mobile sensor (solid dots) on the right hand side can choose to fill one of the two “gaps”. However, without the global network topology information and coordinating with the other mobile sensor, it cannot make an informed decision to form a global barrier.

4. MINIMUM REQUIRED MOVING RANGE

In this section, we first investigate the fundamental limit of the barrier coverage that a mobile sensor network can provide, as well as the requirement on the sensor mobility to reach the limit. We then present an efficient sensor movement scheme that can provide the maximum barrier coverage while minimizing the maximum moving distance among all sensors. Last, we present the simulation results of our sensor movement scheme and compare its performance to a greedy approach.

Sensor movements are often powered by batteries (or local fuel reserve on robots), and normally individual sensors do not share power. Minimizing the total distance traveled by all sensors will minimize total energy cost but will not necessarily lead to balanced power consumption among sensors. On the other hand, minimizing the maximum of distance traveled by any sensor will balance the power consumption among sensors, thus prolonging the network lifetime. For network planning, it is important to find out the minimum required moving range of mobile sensors, as it decides the battery capacity needed to achieve barrier coverage in a mobile sensor network.

4.1 Analytical Results

THEOREM 1. *When m mobile sensors are deployed in a rectangle area of size $\ell \times w$, the maximum number of horizontal barriers that can be formed is*

$$n_b = \lfloor \frac{2mr}{\ell} \rfloor \tag{1}$$

To achieve this limit, the expected minimum of the maximum moving distance among all mobile sensors is

$$d_m = \Theta(\sqrt{\ell r} + w) \ w.h.p. \tag{2}$$

Proof. Each sensor covers a disk area of radius r. In a rectangle area of size $\ell \times w$, a horizontal barrier requires at least $\ell/2r$ sensors to be placed along a line side by side. Therefore, the maximum number of barriers that can be formed is

$$n_b = \lfloor \frac{m}{\ell/2r} \rfloor = \lfloor \frac{2mr}{\ell} \rfloor$$

We consider the following two-phase sensor movement scheme to form k $(k \leq n_b)$ horizontal barriers. These k barriers may be evenly spaced out within the rectangle region, or be located at arbitrary vertical locations according to application requirements.

1. *First Phase (vertical movement)*: sensors move vertically to evenly populate k $(k \leq n_b)$ horizontal lines. After movement, each line will have m/k sensors. The maximum moving distance along the vertical direction is $\Theta(w)$.
2. *Second Phase (horizontal movement)*: sensors move horizontally to their assigned grid points positions (defined below as Y) along the lines.

In the second phase, sensors on each line are initially distributed uniformly at random. To form a barrier, they will need to be relocated to grid points of coordinates $(2i+1)r$, $0 \leq i \leq \ell/2r - 1$. Once every grid point is occupied by a sensor, there is no gap on the line and a barrier is created.

The sensor relocation can be considered as a *minimax grid matching problem* [32], where mobile sensors need to be perfectly matched to the grid points with the coordinates specified above.

Denote the initial sensor locations by

$$X = \{x_1, \ldots, x_{\ell/2r}\},$$

and the grid points on the line by

$$Y = \{y_i = (2i+1)r\}_{i=0}^{\ell/2r-1}.$$

Let $L(X,Y)$ denote the minimum length such that there exists a perfect matching of the points in X to the grid points in Y for which the distance between every pair of matched points is at most $L(X,Y)$. In other words, $L(X,Y)$ is the minimum over all perfect matchings of the maximum distance between any pair of matched points, minimax matching length, and is thus called the *minimax matching length.*

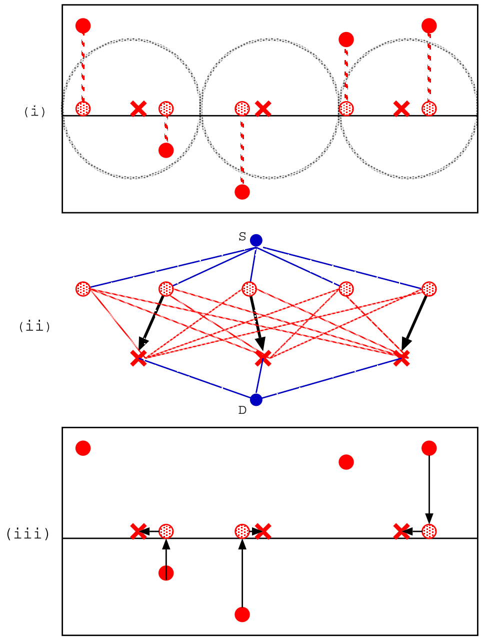

Figure 3: The two-phase sensor movement scheme. Sensors first move vertically to a pre-specified line of defense. They are then assigned to the different grid points, move horizontally to their final locations, and form a barrier.

From [32], for 1-dimensional case where n points are matched to the grid points within [0,1], the expected value of the minimax matching length is $\Theta(1/\sqrt{n})$, i.e., there are positive constants c and C such that

$$c \leq n^{1/2} E[L(X,Y)] \leq C.$$

Applying proper scaling in our model where a number of $\ell/2r$ points are matched to grid points within segment [0, ℓ], we have

$$E[L(X,Y)] = \Theta(\sqrt{\ell r}).$$

Combining the two moving phases, the expected minimax moving distance among all sensors is

$$d_m = \Theta(\sqrt{\ell r} + w) = \begin{cases} \sqrt{lr} & \text{if } w = O(\sqrt{lr}) \\ w & \text{if } w = \omega(\sqrt{lr}) \end{cases}$$

□

Discussions of results:

- In practice, sensors do not need to move in this two-phase (vertical then horizontal) fashion. They can directly move to the final locations in a straight line with a shortened distance. Nevertheless, the two-phase scheme can be used to compute the final location for each sensor. Based on the results, each sensor then moves to its final location in a straight line of distance

$$d = \Theta\left(\sqrt{lr + w^2}\right) = \begin{cases} \sqrt{lr} & \text{if } w = O(\sqrt{lr}) \\ w & \text{if } w = \omega(\sqrt{lr}) \end{cases}$$

The asymptotic behavior of the minimax moving distance remains the same as the two-phase sensor mobility scheme. Therefore, the two-phase sensor mobility scheme is order optimal in achieving the maximum barrier coverage while minimizing the maximum moving distance among sensors.

- Depending on the relative magnitude of w and $\sqrt{lr}$, the minimax moving distance among all sensors is dominated by movement in different directions. Specifically, when $w = O(\sqrt{lr})$, the horizontal movement dominates the total moving distance. Otherwise, when $w = \omega(\sqrt{lr})$, the total moving distance is dominated by the vertical movement.

- If the goal is to minimize the total moving distance of all sensors, a similar matching problem, the *transportation problem*, can be considered. Denote $T(X, Y)$ as the minimum sum of the distance between matched pairs of points in X and Y. It is easily shown that $cn^{1/2} \leq E[T(X, Y)] \leq Cn^{1/2}$, giving the same asymptotic results as in the minimax grid matching problem [32].

4.2 Algorithm Design

We now present a sensor mobility scheme that matches each mobile node to a grid point and minimizes the maximum moving distance among all sensors.

As shown in Figure 3, each mobile sensor first move vertically to its projection on a pre-defined line in the first phase. In the second phase, given the set of mobile sensors S, the grid points Y, and sensor's moving range d, the following algorithm computes if every grid point can be occupied by a mobile sensor under the sensor mobility constraint.

MAX-FLOW(X, Y, d)

1. Construct a bipartite graph $G(V, E)$ ($V = X \cup Y$) as follows. Each vertex in X represents a mobile sensor, and each vertex in Y represents a grid point along the line. $E = \{(u, v), (v, u) | u \in X, v \in Y, \text{ and } dist(u, v) < d\}$.

2. From $G(V, E)$, construct a flow graph $G^*(V^*, E^*)$ and assign capacity to each edge as follows: $\forall$ u $\in$ V, add u to V^*; $\forall$ (u, v) $\in$ E, add (u, v) to E^*. Set *capacity*$(u, v) = 1$ if $u \in X$ and $v \in Y$, otherwise, set *capacity*$(u, v) = 0$. Add a virtual source node S to V^* , and $\forall$ u $\in$ S, add an edge (S, u) to E^*, set *capacity*$(S, u) = 1$; add a virtual sink node D to V^*, and $\forall$ u $\in$ Y of $G(V, E)$, add an edge (u, D) to E^*, set capacity(u, D) = 1.

3. Use a maximum flow algorithm (e.g., Ford-Fulkerson [33]) to compute and return the maximum flow from S to D in G^*.

The Max-Flow algorithm above terminates in $O(VE^2)$ time. When the algorithm terminates, if the returned maximum flow from S to D equals the number of grid points, each grid point will be assigned a sensor and a barrier can be formed. Otherwise, if the returned maximum flow is smaller than the number of grid points, there are not enough sensors to occupy all the grid points, i.e., some grid points will not be occupied by sensors.

Although we assume all nodes are mobile in this case to explore the limit of the barrier coverage that a mobile sensor network can provide, the Max-Flow algorithm can handle the scenario where there are both stationary and mobile sensors. A stationary sensor is equivalent to a mobile node with a zero moving range.

We then use binary search to find the minimax moving distance among all sensors.

```
MINIMAX-MOVING-DISTANCE ($X$, $Y$)
1  $last\_success \leftarrow \ell$; $last\_fail \leftarrow 0$; $d \leftarrow \ell$
2  while ($last\_success$ - $last\_fail \geq \epsilon$)
3        do $f \leftarrow$ MAX-FLOW($X$, $Y$, $d$)
4           if ($f$ = SIZEOF($Y$))
5              then $last\_success \leftarrow d$
6              else $last\_fail \leftarrow d$
7           $d \leftarrow (last\_fail + last\_success)/2$
8  return $d$
```

The above binary search based Minimax-Moving-Distance algorithm terminates in $\Theta(\log \ell)$ iterations. When it terminates, it will return the minimum moving distance that allows every grid point to be occupied by a sensor. The ϵ in line 2 of MINIMAX-MOVING-DISTANCE is a termination threshold. It represents the precision of the d obtained from this algorithm. In each iteration, MAX-FLOW is executed once, so the total running time of the sensor mobility scheme is $O(\log \ell V E^2)$.

4.3 Simulation Results

We now present the performance of the above sensor movement scheme, and compared it with a greedy algorithm. For all the simulation results presented in this paper, each data point is an average of 1000 experiments. The standard deviations of the data points are small and thus not plotted.

4.3.1 Minimax moving distance

We randomly deploy m mobile nodes in a rectangular area of length $2mr$ and width w. As discussed earlier, the maximum moving distance of the vertical movement is $\Theta(w)$. Here we focus on the minimax moving distance of the horizontal movement.

To the best of our knowledge, our paper is the first to explore the fundamental limits of barrier coverage with sensors of limited mobility. There is no prior work which we can directly compare our approach with. To demonstrate the performance of our proposed sensor mobility scheme, we consider a greedy approach and use it as a reference point. The greedy approach tries to assign the closest available mobile sensor to each grid point. Each time we randomly select a grid point that has not assigned a sensor, and assign the closest available mobile sensor to the grid point. This process is repeated until all the grid points are occupied.

Figure 4 compares the minimax moving distance of our scheme with that of the greedy algorithm. As the length of the field increases, the minimax moving distance of the greedy algorithm grows linearly, while in our scheme the growth is sub-linear, resulting in a widening gap between the two approaches.

According to Theorem 1, the minimax moving distance (d_m) in our scheme is proportional to the square root of the length (ℓ), i.e., $d_m = \Theta(\ell^{0.5})$. This is confirmed by the regression results, as shown in Figure 4. For example, the simulation results for the case $r = 20$ can be well

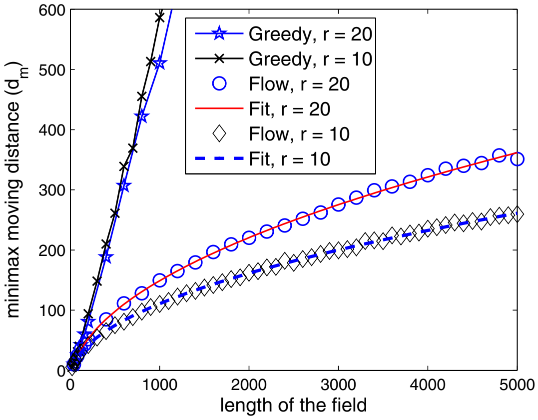

Figure 4: Minimax moving distance to achieve barrier coverage.

fitted by $d_m = a\ell^b + c$, where $a = 5.8934$, $b = 0.4919$, and $c = -27.4322$. The 95% confidence interval of b is [0.4749, 0.5090].

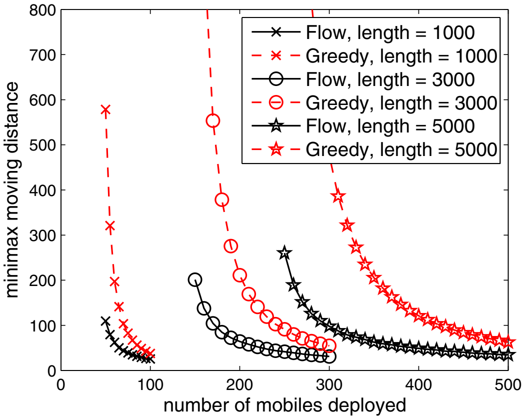

Figure 5: Minimax moving distance with redundant mobile sensors.

4.3.2 *Effect of redundant mobile sensors*

In the above experiments, the number of sensors is the minimum required to achieve barrier coverage. There is no redundant sensors. In practice, redundant sensors are often deployed to improve the robustness and prolong the lifetime of a network. It is interesting to see how our algorithm performs when there are more mobile sensors than the minimum requirement to achieve barrier coverage.

In the experiments, we consider three network scenarios where the length of the field is set to be 1000, 3000, and 5000, respectively. The sensing range of a sensor is fixed at 10. Therefore, the minimum required number of sensors to achieve barrier coverage in each scenario is 50, 150, and 250, respectively. We vary the number of mobiles deployed for each scenario from its minimum required number to twice as much.

As shown in Figure 5, the minimax moving distance to achieve barrier coverage decreases as more redundant mobile sensors are added. For comparison, we also plot the minimax moving distance obtained from greedy approach for the same settings. The gap between the greedy approach and our algorithm narrows as more sensors are deployed. The reason is that as the number of redundant nodes increases, there will be more nodes nearby to choose from for each grid point in the greedy algorithm. Consequently, the results obtained by the greedy algorithm will be close to the optimal approach. However, this happens only when there is a large number of redundant nodes. Our algorithm outperforms the greedy approach by a large margin when there is no significant large number of redundant nodes.

5. MOBILITY IMPROVES BARRIER COVERAGE

In this section, we study the impact of sensor mobility on the barrier coverage probability. The mobility characteristics of a sensor network include the ratio of mobile sensors among all the sensors, and the moving range of these mobile sensors. The results will help network planners choose appropriate parameters to ensure barrier coverage for a given network scenario.

5.1 Effect of Node Mobility on Percolation Threshold

In [4], the barrier coverage of a two-dimensional sensor network is related to the existence of a giant sensor cluster that percolates the network. According to percolation theory [34], in a network where sensors are located according to a Poisson point process of density λ, there exists a critical density λ_c where a phase transition occurs with respect to the size of the largest sensor cluster.

If the node density is below the critical density, i.e., $\lambda < \lambda_c$, all sensor clusters are finite in size almost surely and there is no percolation. There exists an uncovered region where an intruder can penetrate the network without being detected. When the node density is above the critical density, i.e., $\lambda \geq \lambda_c$, an unbounded sensor cluster emerges to percolate the whole network, acting as a “trip wire” that can detect any intruders crossing the network. The critical condition for the existence and strength of barrier coverage is further studied for a two-dimensional rectangle sensor network in [6].

When some or all of the sensors are mobile, these mobile sensors can move to desired locations, bridging isolated sensor clusters together to form a global cluster, as has been illustrated in Figure 1. This will lower the percolation threshold and improve the number of disjoint sensor barriers. For a given total number of sensors, the more mobile sensors, the lower the percolation threshold. The extent that the percolation threshold is lowered would depend on the fraction of sensors that are mobile as well as their moving ranges. In the extreme case, when all sensors are mobile and the moving range is not a limiting factor, sensors can move to line up side-by-side to provide maximum number of disjoint barriers.

Analysis on the continuum percolation threshold under the Poisson point process is a challenging task [34]. We use simulations to confirm the above arguments on the effect of node mobility on the percolation threshold. In the simulation, sensors are initially deployed in a rectangle region of size 1000 × 100 uniformly at random. The sensing range of each sensor is set to be 10 and the moving range of each sensor is set to be 30. We vary the fraction of mobile sensors to examine the effect of node mobility on the percolation threshold which is equivalent to the barrier coverage probability.

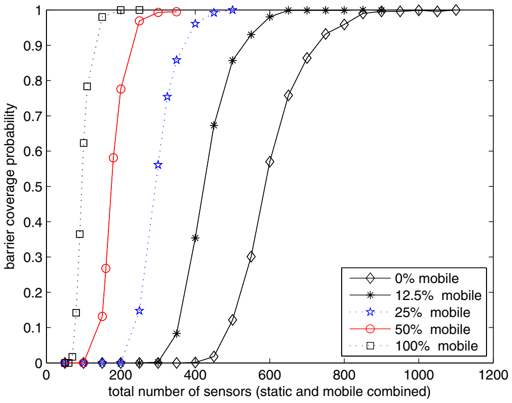

Figure 6: Effect of node mobility on the percolation threshold (barrier coverage probability).

Figure 6 shows how the percolation threshold (barrier coverage probability) is lowered when a fraction of the sensors become mobile. In the figure each data point represents the average of 1000 repeated experiments. The different curves correspond to different fraction of mobile sensors, 0%, 12.5%, 25%, 50%, and 100%. We observe that for each curve, there is a “phase transition” at some point where the barrier coverage probability quickly increases from 0 to 1. For each curve the transition point represents the percolation threshold. As the fraction of mobile sensors increases, the percolation threshold decreases. We also observe that as the fraction of mobile sensors further increases, the rate that the percolation threshold decreases slows down. This is likely because many opportunities to connect local sensor clusters so as to form a global cluster have already been explored. Further increasing the fraction of mobile sensors will not result in significant gain.

5.2 Barrier Coverage with Mobile Sensors

A mobile sensor can move to any location within its moving range. In our algorithm, we restrict its movement to discrete grid points. A mobile sensor initially deployed at (x_0, y_0) can be relocated to any grid point within a circle of radius R. The candidate locations are $(x \pm di, y \pm dj)$ for integers i,j satisfying $(i^2 + j^2) \leq \frac{R^2}{d^2}$ where d is the unit length of the grids. We recognize that the discretization of candidate locations introduces a deviation between the optimal desired location and final location produced by our algorithm. Nevertheless, this deviation is upper bounded by d. Thus its impact on the performance of the algorithm depends on the grid size d. When $d \ll R$ and $d \ll r$, we expect the detrimental effect caused by the discretization of sensor movement to be minimum. This is confirmed by our simulation results.

We first construct a graph that accounts for both the stationary sensors and the candidate locations that mobile sensors can move to. An edge is added between two nodes in the graph if they are not candidate locations for the same mobile node and the distance between them is within $2r$. We then use a depth-first-search based algorithm to test if a rectangular area is barrier covered. Our algorithm is a centralized approach and works for network scenarios with arbitrary combinations of stationary and mobile sensors.

1. Construct a graph $G = (V, E)$, $V = V_1 \cup V_2, V_1 \cap V_2 = \emptyset$ as follows. Each vertex in V_1 represents a stationary sensor, and $V_2 = \cup_{i,j}\{u_{ij}\}$ where u_{ij} is the j-th candidate location of mobile node i. $E = \{(u, v)|\forall u, v \in V$, u and v are not candidate locations for the same mobile node; $distance(u, v) \leq 2r$, where r is the sensing range of each sensor.$\}$.
2. Construct a graph $G^* = (V^*, E^*)$. $V^* = V \cup \{S, D\}$, $E^* = E \cup \{(S, u)|u \in V$ intersects the left boundary of the rectangular area$\}$ $\cup\{(u, D)|u \in V$ intersects the right boundary of the rectangular area$\}$.
3. Perform Mobile-Barrier on G^*. If it returns SUCCESS, the area is barrier covered. Otherwise, no barrier can be formed with current network setting.

The following Mobile-Barrier algorithm tests if there exist a sensor barrier across the deployed region that accounts for the sensor mobility by considering all the candidate locations of mobile sensors.

```
Mobile-Barrier ($G$)
1   color all nodes in $G$ as WHITE
2   $m_i \leftarrow$ UNBLOCKED, for $i = 1, .., |m|$
    ▷ mark all mobile nodes unblocked
3   initiate $stack$ as an empty Stack
4   $stack$.push($S$)
5   color $S$ as GRAY
6   while ($stack$ is not empty)
7       do $u \leftarrow stack$.top()
8          if ($u = D$)
9             then return SUCCESS
10         for any neighbor $v$ of $u$
11             do if ($v$ is stationary nodes ) and ($v$ is WHITE)
12                   then $stack$.push( $v$)
13                        color $v$ as GRAY
14                        break
15                if ($v$ is a candidate position of a mobile node $i$)
                  and ($m_i$ = UNBLOCKED)
                  and ($v$ is WHITE)
16                   then $stack$.push($v$)
17                        color $v$ as GRAY
18                        $m_i \leftarrow$ BLOCKED; ▷ mark mobile $i$ blocked
19                        break
20         ▷ end of for
21         if ($u = stack$.top()) ▷ nothing is pushed into stack
22            then $stack$.pop()
23                 color $u$ as BLACK
24                 if ($u$ is a candidate location of mobile node $i$)
25                    then $m_i \leftarrow$ UNBLOCKED
                           ▷ mark mobile $i$ unblocked
26  ▷ end of while
27  return FAILURE
```

To guarantee that a mobile sensor can only move to one of its candidate final locations, a variable is introduced (line 2) for each mobile sensor to mark if one of its candidate locations has been used. In line 18 and 25, the variable is used to block or free the use of a mobile sensor. In line 15, when considering to whether to visit a node, we check not only if this node has been visited, but also if any of its sibling candidate positions have been blocked.

If the above search algorithm terminates with SUCCESS, there exists a connected sensor cluster spanning from the left boundary to the right boundary of the region after the selected mobile sensors move to their computed final locations. The elements in the stack constitute a sequence of sensors forming a barrier. If the algorithm returns FAILURE, no barrier can be formed no matter what location each mobile sensor moves to. Figure 7 shows an example for the execution of the Mobile-Barrier algorithm on a small network with one mobile node.

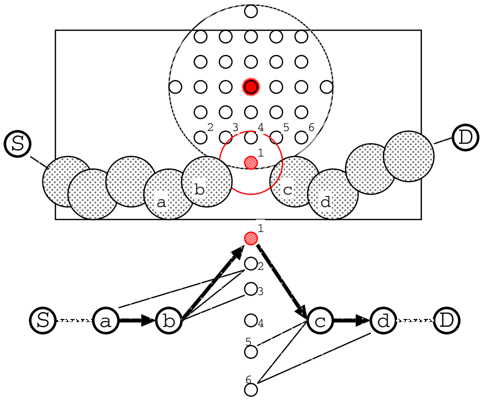

Figure 7: Example of the execution of Mobile-Barrier algorithm. The mobile node is assigned to move to candidate position 1 to form a barrier.

In the network there are n stationary sensors and m mobile sensors with each mobile sensor having $k \approx \frac{\pi R^2}{d^2}$ candidate locations. In the worst case, the **while** loop iterates through each stationary sensor once and examines each mobile sensors k times at its k candidate locations. Based on the complexity of depth-first-search, the algorithm above terminates in $O(n + km)$ time.

This algorithm is centralized, due to the global nature of the barrier coverage problem. However, in [6], a divide-and-conquer approach has been proposed to efficiently build barriers in a large sensor network. For a large network, we can adopt this approach to divide a long strip into short segments, and run the Mobile-Barrier algorithm on these small segments.

5.3 Simulation Results

5.3.1 *Effect of moving range*

We first study the effect of maximum sensor moving range on the probability of barrier coverage. We deploy 100 mobile sensors uniformly at random in four different rectangle settings, 1500×100, 1200×100, 1000×100, 800×100. Every sensor has a sensing range of 10. Figure 8 plots barrier coverage probability as a function of sensor's moving range.

It can be observed that for each of the four scenarios, there is no barrier coverage upon initial deployment. As the sensor moving range increases to a certain level, the barrier coverage probability starts to improve. As the moving range further increases, sensors can travel farther and more barriers can be formed, resulting in a rapid increase of the barrier coverage probability. The improvement slows down and eventually levels off after a certain point. Also, for different rectangle settings, a longer rectangle requires a larger sensor moving range to achieve barrier coverage. This is consistent with the analytic results presented in 4.1.

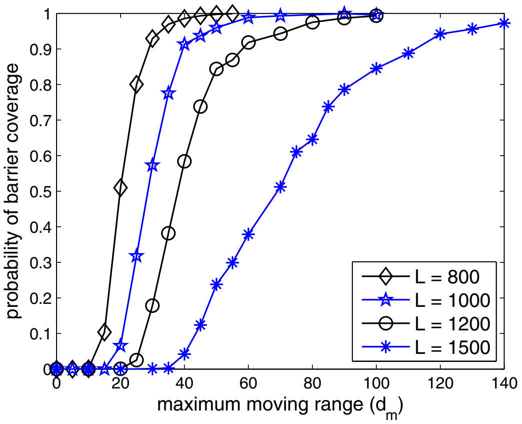

Figure 8: Effect of sensor moving range on the barrier coverage probability.

It is worth mentioning that, for a rectangular area of 1000×100, a minimum of 50 sensors is needed to achieve barrier coverage if the sensing range of each sensor is 10. This is achieved when the 50 sensors are lined up side by side across the rectangle. Without any mobility, our simulation shows that at least 850 sensors are needed if they are deployed in the same rectangle uniformly at random. When mobile sensors are deployed uniformly at random, Figure 8 shows that the barrier coverage can be achieved by 100 mobile sensors with a moving range of $R = 60$ after movement. This indicates a significant efficiency improvement introduced by sensor mobility.

5.3.2 *Effect of ratio of mobile sensors*

The effect of the ratio of mobile sensors on the barrier coverage is similar to that of the moving range. In this experiment, we randomly deploy a total number of 100 sensors in a rectangular area of size 500×50. Among the 100 sensors, the number of mobile sensors varies from 0 to 100. The sensing range of each sensor is set to be 10. We consider four different maximum moving ranges $R = 10$, 20, 30, and 40. Figure 9 shows the relation between barrier coverage probability and ratio of mobile sensors in the network.

As can be observed from Figure 9, when only stationary sensors are deployed, barrier coverage cannot be achieved with the 100 sensors. As we increase the ratio of mobile sensors, the probability of successfully forming a barrier starts to increase after a certain level, then rises up rapidly and eventually levels off to 1. This result is important for network planners, as it shows the benefit of additional investment (deploying a larger ratio of mobile sensors) varies at different regimes. In the sharp increase part of the curve, additional investment will lead to significant improvement in barrier coverage. However, after the curve levels off, the improvement will slow down with the additional investment. For a fixed ratio of mobile sensors, the setting with larger moving range always yields higher probability of barrier cover.

6. CONCLUSION

In this paper, we study the barrier coverage with mobile sensors of limited mobility. Through mathematical analysis,

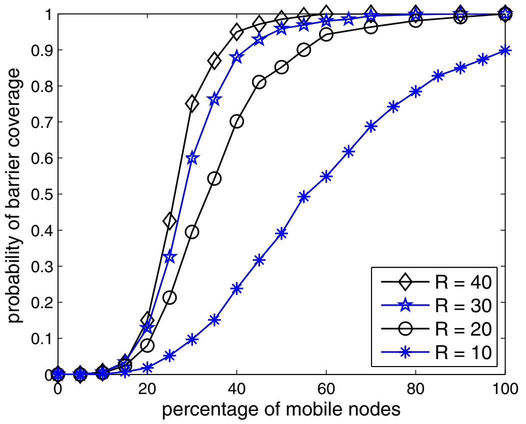

Figure 9: Effect of percentage of mobile sensors on the barrier coverage probability.

we first explore the fundamental limits of the barrier coverage under sensor mobility. We present an efficient sensor mobility scheme that achieves the maximum barrier coverage and minimizes the maximum sensor moving distance. We then show that sensor mobility can effectively lower the percolation threshold of the network, and thus improve the barrier coverage probability. We further devise an algorithm that computes the existence of barrier coverage under the limited sensor mobility constraint, and constructs a barrier should it exist. Through extensive simulations we examine the impact of sensor mobility on barrier coverage. Our results show that the fraction of mobile sensors or the moving range of mobile sensors has to reach a certain level before the barrier coverage starts to improve. After this, the improvement rises rapidly and levels off after all possible new barriers are formed. Our results serve as guidelines to network planers and help build stronger and more efficient barrier coverage applications.

7. ACKNOWLEDGMENTS

We thank the anonymous reviewers for their helpful comments and Professor Cecilia Mascolo for shepherding our paper. This research was partly supported by the National Science Foundation under grant numbers CNS-0721626, CNS-0953620, and CNS-0954039.

8. REFERENCES

[1] A. A. Somasundara, A. Ramamoorthy, and M. B. Srivastava, “Mobile element scheduling with dynamic deadlines,” *IEEE Transactions on Mobile Computing (TMC)*, vol. 6, no. 4, pp. 1142–1157, 2007.

[2] K. Dantu, M. Rahimi, H. Shah, S. Babel, A. Dhariwal, and G. S. Sukhatme, “Robomote: enabling mobility in sensor networks,” in *Proc. IEEE International Conference in Infomation Processing in Sensor Network(IPSN)*, 2005.

[3] “Khepera robots,” http://www.k-team.com.

[4] B. Liu and D. Towsley, “A study on the coverage of large-scale sensor networks,” in *The 1st IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS)*, 2004.

[5] S. Kumar, T. H. Lai, and A. Arora, “Barrier coverage with wireless sensors,” in *Proc. ACM International Conference on Mobile Computing and Networking (Mobicom)*, 2005.

[6] B. Liu, O. Dousse, J. Wang, and A. Saipulla, “Strong barrier coverage of wireless sensor networks,” in *Proc. of The ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc)*, 2008.

[7] A. Chen, T. H. Lai, and D. Xuan, “Measuring and guaranteeing quality of barrier-coverage in wireless sensor networks,” in *Proc. of The ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc)*, 2008.

[8] A. Saipulla, C. Westphal, B. Liu, and J. Wang, “Barrier coverage of line-based deployed wireless sensor networks,” in *Proc. of IEEE Conference on Computer Communications (InfoCom)*, 2009.

[9] G. Yang and D. Qiao, “Barrier infomation coverage with wireless sensor,” in *Proc. of IEEE Conference on Computer Communications (InfoCom)*, 2009.

[10] A. Howard, M. Mataric, and G. Sukhatme, “Mobile sensor network deployment using potential fields: A distributed, scalable solution to the area coverage problem,” in *DARS 02*, 2002.

[11] Y. Zou and K. Chakrabarty, “Sensor deployment and target localization based on virtual forces,” in *Proc. of IEEE Conference on Computer Communications (InfoCom)*, 2003.

[12] G. Wang, G. Cao, and T. L. Porta, “Movement-assisted sensor deployment,” in *Proc. of IEEE Conference on Computer Communications (InfoCom)*, 2004.

[13] S. Chellappan, W. Gu, X. Bai, D. Xuan, B. Ma, and K. Zhang, “Deploying wireless sensor networks under limited mobility constraints,” *IEEE Transactions on Mobile Computing (TMC)*, vol. 6, no. 10, pp. 1142–1157, 2007.

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

[15] S. Meguerdichian, F. Koushanfar, M. Potkonjak, and M. B. Srivastava, “Coverage problems in wireless ad-hoc sensor networks,” in *Proc. IEEE Conference on Computer Communications (Infocom)*, 2001, pp. 1380–1387.

[16] S. Meguerdichian, F. Koushanfar, G. Qu, and M. Potkonjak, “Exposure in wireless ad-hoc sensor networks,” in *ACM Mobile Computing and Networking*, 2001, pp. 139–150.

[17] X.-Y. Li, P.-J. Wan, and O. Frieder, “Coverage in wireless ad-hoc sensor networks,” *IEEE Transactions on Computers*, vol. 52, no. 6, pp. 753–763, June 2003.

[18] G. Veltri, Q. Huang, G. Qu, and M. Potkonjak, “Minimal and maximal exposure path algorithms for wireless embedded sensor networks,” in *Proc. of ACM Conference on Embedded Networked Sensor Systems (Sensys)*, 2003.

[19] T. Clouqueur, V. Phipatanasuphorn, P. Ramanathan, and K. K. Saluja, “Sensor depolyment strategy for detection of targets traversing a region,” *ACM Mobile Networks and Applications*, vol. 8, pp. 453–461, 2003.

[20] H. M. Ammari and S. K. Das, “Coverage and

connectivity in three-dimensional wireless sensor networks using percolation theory," *IEEE Transactions on Parallel and Distributed Systems*, vol. 20, no. 6, pp. 872–885, 2009.

[21] S. Barr, B. Liu, and J. Wang, "Underwater barriers with sensor networks using auction algorithms," in *Proc. of Intl. Conf. on Computer Communications and Networks (ICCCN)*, 2009.

[22] A. Chen, S. Kumar, and T.-H. Lai, "Designing localized algorithms for barrier coverage," in *Proceedings of ACM International Conference on Mobile Computing and Networking (Mobicom)*, 2007.

[23] G. Yang and D. Qiao, "Multi-round sensor deployment for guaranteed barrier coverage," in *Proc. IEEE Infocom*, 2010.

[24] A. Saipulla, B. Liu, and J. Wang, "Barrier coverage with airdropped sensors," in *Proc. of IEEE International Conference for Military Communications (MilCom)*, 2008.

[25] E. Amaldi, A. Capone, M. Cesana, and I. Filippini, "Coverage planning of wireless sensors for mobile target detection," in *Proc. of IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS)*, 2008.

[26] C. Shen, W. Cheng, X. Liao, and S. Peng, "Barrier coverage with mobile sensors," in *Proc. of IEEE The International Symposium on Parallel Architectures, Algorithms, and Networks (ISPAN)*, 2008.

[27] B. Liu, P. Brass, O. Dousse, P. Nain, and D. Towsley, "Mobility improves coverage of sensor networks," in *Proc. of The ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc)*, 2005.

[28] G. Yang, W. Zhou, and D. Qiao, "Defending against barrier intrusions with mobile sensors," in *Proc. of IEEE International Conference on Wireless Algorithms, Systems, and Applications (WASA)*, 2007.

[29] R. Tan, G. Xing, J. Wang, and H. C. So, "Exploiting reactive mobility for collaborative target detection in wireless sensor networks," *IEEE Transactions on Mobile Computing (TMC)*, vol. 9, no. 3, pp. 317–332, 2010.

[30] G. Xing, J. Wang, Z. Yuan, R. Tan, L. Sun, Q. Huang, X. Jia, and H. C. So, "Mobility-assisted spatiotemporal detection in wireless sensor networks," *IEEE Transactions on Parallel and Distributed Systems*, preprint 2010.

[31] G. Xing, X. Wang, Y. Zhang, C. Lu, R. Pless, and C. D. Gill, "Integrated coverage and connectivity configuration for energy conservation in sensor networks," *ACM Transactions on Sensor Networks*, no. 1, 2005.

[32] P. Shor and J. Yukich, "Minimax grid matching and empirical measures," *The Annals of Probability*, vol. 19, no. 3, pp. 1338–1348, 1991.

[33] T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein, *Introduction to Algorithms (Second Edition)*. MIT Press and McGraw-Hill, 2001.

[34] R. Meester and R. Roy, *Continuum percolation*. Cambridge University Press, 1996.