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REVIEW ARTICLE

A survey on barrier coverage with sensors

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Abstract For various applications, sensors are deployed to monitor belt regions to guarantee that every movement crossing a barrier of sensors will be detected in real-time with high accuracy and minimize the need for human support. The barrier coverage problem is introduced to model these requirements, and has been examined thoroughly in the past decades. In this survey, we state the problem definitions and systematically consider sensing models, design issues and challenges in barrier coverage problem. We also review representative algorithms in this survey. Furthermore, we provide discussions on some extensions and variants of barrier coverage problems.

Keywords sensor network, barrier coverage

1 Introduction

Recent advances in micro-electro-mechanical systems technology, wireless communications, computing and sensor technology have enabled the rapid development of low-cost, small-size sensor nodes that integrate sensing, data processing and wireless communication [1,2]. Although sensor nodes are usually resource limited, such as limited battery, memory and computation capacities, they can collaborate with each other to accomplish big tasks efficiently. A typical wireless sensor network (WSN) consists of thousands of sensor nodes deployed in the region of interest (ROI), which can be used to monitor physical phenomena of the ROI. The unique features of WSNs, such as randomly deployment, and self-organization, have ensured a wide range of applications for sensor networks including battlefield surveillance, environmental monitoring, homeland security, health monitoring and so on.

Intruder detection is one of the most important applications of WSNs, the purpose of which is to detect any intruder that attempts to penetrate the ROI. In reality, lots of security applications need to detect intruders, such as national border protection, critical resource protection, and disaster warning. It is worth noting that in order to detect intruders penetrating the ROI, it is not necessary to guarantee that every point in the ROI is covered by one or multiple sensor nodes. Therefore, traditional full area coverage model is not suitable for intruder detection any more. In contrast, a new coverage model, barrier coverage [3], was proposed specifically for intruder detection in WSNs where sensing regions of sensor nodes form one or multiple barriers so that every intruder crossing the ROI will be detected. Compared to full area coverage, barrier coverage can efficiently detect intruders with much less sensor nodes.

Due to its advantage for security applications, barrier coverage has received extensive attentions in recent years. Earlier researches mainly focused on critical condition analysis (e.g., sensor node density) and barrier construction for stationary sensors with omnidirectional sensors [3,4]. Later, several dedicated and widely-used sensors such as camera, radar were taken into consideration, and directional sensing model was extensively considered in barrier coverage problem. With the development of mobile sensor nodes, they are used to improve the quality of barrier coverage and reduce the cost of sensor node deployment. Meanwhile, barrier coverage with different sensing models, such as full-view cov-

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erage model and probabilistic sensing model, were also proposed and studied. In this paper, we provide a comprehensive survey of barrier coverage including definitions, terminologies, state-of-the-art algorithms and applications, and discuss open research issues in details.

The remainder of this paper is organized as follows. We describe the definitions and terminologies of barrier coverage in Section 2. We introduce several commonly used sensors in various security applications and present their sensing models in Section 3. We provide the state-of-the-art algorithms of barrier coverage in Section 4. Open research issues are discussed in Section 5. Finally, we conclude the paper in Section 6.

2 Problem of barrier coverage

We know that a barrier is a belt region deployed with a set of sensors to detect intruders' attempts to cross the region. In this section, we systematically consider the region of interest and intruders, and give an overview of the problem of barrier coverage and terminologies.

2.1 Region of interest

In barrier coverage, the region of interest (RoI) is often a long belt region, which is the boundary of the protected area. Sensors are deployed in the RoI to detect intruders that attempt to cross the belt region into the protected area. The RoI is usually assumed to be a two-dimensional belt region that is bounded by two parallel lines. As shown in Fig. 1, the RoI may be a closed belt region or an open belt region, which is described as follows.

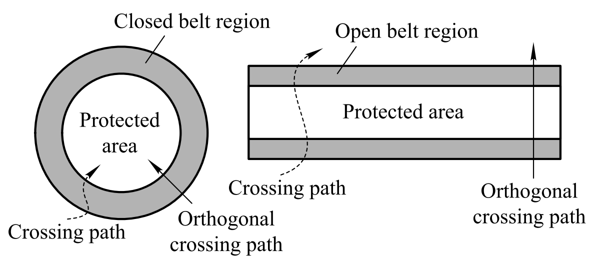


Fig. 1 Region of interest (RoI) and crossing path

- **Closed belt region** is a closed belt region having no boundaries. Ring belt is one of the common closed belt.
- **Open belt region** is a belt region with two boundaries orthogonal to the two parallel lines. For ease of presentation, one of the orthogonal boundaries is referred to as the left boundary and the other the right boundary. Rectangle belt is one of the common open belt studied in existing literatures.

For both closed belt region and open belt region, we can formally define them according to [3]. Before introducing the definition of the belt region, we first give some notations used in this survey. Let $\|\mathbf{xy}\|$ denote the Euclidean distance between two points $\mathbf{x}$ and $\mathbf{y}$; and for a point $\mathbf{x}$ and a curve ℓ, let $\|\mathbf{x}\ell\|$ be the distance between $\mathbf{x}$ and ℓ, which is the smallest distance between $\mathbf{x}$ and any point $\mathbf{y}$ on ℓ, i.e., $\|\mathbf{x}\ell\| = \min\{\|\mathbf{xy}\| | \mathbf{y} \in \ell\}$. Two curves ℓ_1 and ℓ_2 are said to be *parallel* with separation s, if $\|\mathbf{x}\ell_2\| = \|\mathbf{y}\ell_1\| = s$, for all $\mathbf{x} \in \ell_1$ and $\mathbf{y} \in \ell_2$. We now give the definition of a belt region as follows.

Definition 1 (Belt of dimension $\mathcal{B}(\lambda_1, \lambda_2, s)$ [3]) Two curves ℓ_1 and ℓ_2 are uniformly separated with separation s if $\|\mathbf{x}\ell_2\| = \|\mathbf{y}\ell_1\| = s$, for all points $\mathbf{x} \in \ell_1$ and $\mathbf{y} \in \ell_2$. A region bounded by two curves ℓ_1 and ℓ_2, which are uniformly separated with separation s and are of lengths λ_1 and λ_2 respectively, is referred to as a belt of dimension $\mathcal{B}(\lambda_1, \lambda_2, s)$, in which s is referred to as the belt's width and λ_1 and λ_2 its lengths.

According to the definition, a rectangular region is said to be a belt of dimension $\mathcal{B}(s, s, 1/s)$, if its length is s and width is $1/s$. This can also be denoted by $\mathcal{B}_s$. A belt with dimension $\mathcal{B}(2\pi r_1, 2\pi r_2, r_2 - r_1)$ is a ring region between the two concentric circles of radius r_1 and r_2, where $r_1 < r_2$.

For a belt region defined above, the concept of k-full coverage [5] is widely used, which means that every point in the deployment region is covered by at least k distinct sensors. However, this is a very strong requirement and is normally not necessary in barrier coverage, since there is no need to monitor a path by covering every point on it by k distinct sensors. In contrast to k-full coverage, k-barrier coverage is normally good enough to detect intruders. A crossing path[1)] ℓ is said to be k-barrier covered, if it is covered by at least k distinct sensors. A belt region is said to be *k-barrier covered*, if and only if all crossing paths through the belt are k-covered by the deployed sensor network [3].

It has been proven that it is not possible to locally determine whether a given region is k-barrier covered or not [3]. The problem of determining whether or not a given belt region is k-barrier covered depends on the style of the belt region.

- The condition for an open belt region to be k-barrier

[1)] Please refer to the definition in Section 2.2.1

covered can be reduced to the problem of determining whether there exist k node-disjoint paths between a pair of vertices in a graph of $|V|$ nodes, which can be solved using the best-known algorithm with complexity $O(k^2|V|)$ [6].

- The problem of determining whether a closed belt region is k-barrier covered can be reduced to the problem of determining whether there exist k node-disjoint cycles, each of which loops around the entire belt region. According to [6], there exists a polynomial time algorithm to determine whether there exist k node-disjoint cycles in the coverage graph corresponding to a sensor network deployed over a closed belt region.

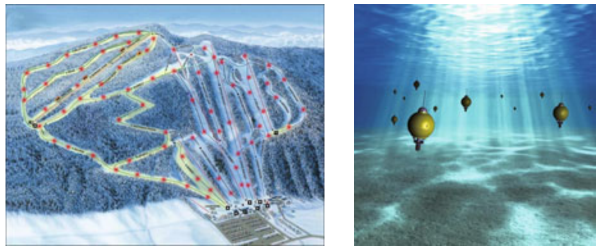
We note that for a belt region, the optimal configuration for achieving k-barrier coverage is to deploy k rows of sensors along a shortest path (line or curve) across the region, where each path has consecutive sensors' sensing disks abutting each other.

Theorem 1 (Necessary and sufficient condition for k-barrier coverage [6]) We consider a belt region $\mathcal{B}$, and let s denote the length of the shortest path across the region. Then, the number of sensors necessary and sufficient to achieve k-barrier coverage in this region is $k \times \lceil s/(2r) \rceil$; if two sensing disks D_1 and D_2 have overlap, then $(D_1 \cup D_2) \cap \mathcal{B}$ is a connected sub-region in the belt region.

However, the problem of determining an optimal configuration for achieving full k-coverage for general values of k is still an open problem [3]. A asynchronous distributed algorithm is presented to find the maximum number of disjoint sensor barriers in wireless sensor networks [7]. It utilizes the property of wireless channel and has lower complexity compared with other algorithms. For a deployment of n sensors, the algorithm spends $O(n^2)$ messages and $O(n^2)$ time.

In most of the existing work, one basic assumption is that the RoI is two-dimensional. However, this is not sufficient for many real world environments. As shown in Fig. 2, sensors deployed on the mountain, in the atmosphere, the sea, and outer space may need to guarantee the barrier covered in three-dimensional space. In this scenario, previous approaches may not work, and we need to re-examine barrier coverage problem. Although the problem of 3-dimensional barrier coverage for underwater sensor networks was studied by Barr et al. [8], barrier coverage in three dimension RoI is still an open problem.

In the state-of-the-art studies, most of the work regards the RoI as a static area, and do not work when protected area are moving, such as marching troop and orbiters. The problem of mobile barrier coverage (MBC) with dynamic objects was first discussed by Kong et al. [9]. They proposed a fully distributed algorithm for mobile sensor nodes to cooperatively move and maintain the high-quality barrier coverage.



(a) (b)

Fig. 2 Sensors deployed in three-dimensional space. (a) On the mountain; (b) in the sea

2.2 Intruders

2.2.1 Crossing path

A crossing path is a path that connects the RoI to the opposite side, where the ingress point and the egress point reside on two opposite sides of the region [10]. For a two-dimensional belt, orthogonal crossing paths are straight lines, whose length is equal to the belt's width, as shown in Fig. 3.

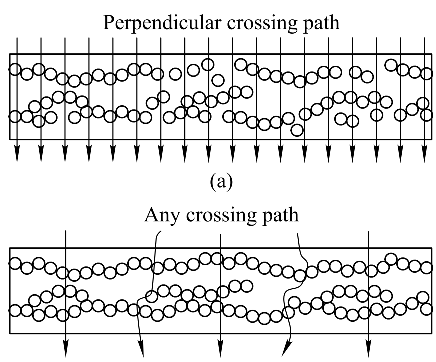


Fig. 3 (a) Weak 2-barrier coverage and (b) Strong 2-barrier coverage

Kumar et al. defined two types of barrier coverage, namely weak and strong barrier coverage [3], which guarantee to detect intruders moving along congruent paths and all crossing paths, respectively. To formally define these two concepts, we first introduce the concept of k-barrier coverage modulo ℓ.

Definition 2 (k-barrier coverage modulo ℓ [3]) Let $\mathcal{B}$ be a belt region with a sensor network deployed over it, and ℓ be a crossing path through $\mathcal{B}$. $\mathbb{L}(\ell)$ denote the set of all crossing paths congruent to ℓ. $\mathcal{B}$ is said to be k-barrier covered modulo ℓ if and only if $Pr[\forall i \in \mathbb{L}(\ell) : A_k(i)] = 1$; i.e., every path in $\mathbb{L}(\ell)$ is k-covered by the sensor network.

We say that event $T(n)$ occurs with high probability (w.h.p.) if $\lim_{n\to\infty} Pr[T(n)] = 1$. The definition of weak and strong k-barrier coverage are described as follows.

Definition 3 (Weak k-barrier coverage w.h.p. [3]) Let $\mathcal{B}_s$ be a belt region of dimension $(s, s, 1/s)$ or $(\lambda_1, \lambda_2, 1/s)$ with a sensor network $N(n, r)$ deployed over it. Let ℓ be a crossing path through $\mathcal{B}_s$.
$\mathcal{B}_s$ is said to be weakly k-barrier covered w.h.p. if and only if

$$\forall \ell : \lim_{s\to\infty} Pr[\mathcal{B}_s \text{ is } k\text{-barrier covered modulo } \ell] = 1.$$

$\mathcal{B}_s$ is said to be strongly k-barrier covered w.h.p. if and only if

$$\lim_{s\to\infty} Pr[\forall \ell : \mathcal{B}_s \text{ is } k\text{-barrier covered modulo } \ell] = 1.$$

It has been shown in [3] that this distinction between strong and weak barrier coverage w.h.p. is that if a region is strongly barrier covered w.h.p.. Then even if the intruders can see the location of sensors, w.h.p. they cannot cross the RoI without being detected. On the other hand, if the region is weakly barrier covered w.h.p., then all intruders will be detected w.h.p. if they cannot see the sensors. However, if the region is weakly barrier covered w.h.p. and if the sensor network is not stealthiness, then an intruder may be able to find an uncovered path through the region.

Among all the crossing paths between a source and a destination, two specific kinds of paths captured our attention, namely maximal support paths and maximal breach paths [11]. The maximal support path between a source and a destination is a path such that the maximum distance from every point on it to the sensors is minimized. This path is most likely to be detected by the deployed sensors. Accordingly, the maximal breach path is defined as a path between a source and a destination which maximizes the minimum distance from every point on it to the sensors. This is the hardest path to detect by the deployed sensors. Two polynomial-time approaches were proposed to find the optimal solutions for both the maximum k-support coverage problem and the minimum k-breach coverage problem [12]. The time complexity of both algorithms are $O(k^2 n \log n)$, where n is the number of deployed sensor nodes and k is the coverage degree.

For some intrusion detection applications, it may be the case that only one direction of crossing (the belt) is illegal and previous work may leads to a lot of false alarms. Therefore, a new coverage model called one-way barrier coverage, which requires that the network reports illegal intruders while ignores legal ones, was proposed and investigated by Chen et al. [13]. Their research illustrated that it is not straightforward to provide a one-way barrier coverage, even though there is only one intruder. When there are multiple intruders, the concept of neighboring barriers was introduced and different protocols were designed to provide one-way barrier coverage for different sensor models based on neighboring barriers.

2.2.2 Knowledge of sensors

A sensor network is said to be *stealthiness* if no intruder is aware of the locations of the sensors [3]. One such example is the wireless underground sensor network (WUSN), which will be shown in Section 3.1.1. It was proved that if a sensor network is stealthiness, the optimal crossing paths that minimize the probability of being detected in a two-dimensional rectangular network are the orthogonal crossing paths [14].

2.2.3 Distribution of intruders

In many application scenarios, there is a temporal correlation between intruder arrival times [15], e.g., when an intruder arrives, the probability that another intruder arrives again in the next few time slots becomes small. Thus, intruders are assumed to arrive stochastically at each point of RoI, and the intruder inter arrival time t is a random variable with a distribution of cumulative function $F(t)$ at any point. Weibull distribution well characterizes this temporal correlation of the intruder arrival time, and has been widely adopted to model many real world random events [16]. The density function $f(t)$ and cumulative function $F(t)$ functions of a Weibull distribution are given by

$$f(t) = \frac{\beta}{\lambda}\left(\frac{t}{\lambda}\right)^{\beta-1} e^{-(\frac{t}{\lambda})^{\beta}},\ F(t) = 1 - e^{-(\frac{t}{\lambda})^{\beta}},$$

where $x \geqslant 0$, $\lambda > 0$, and $\beta \geqslant 1$. We note that when $\beta = 1$, Weibull distribution becomes the well-known Poisson distribution.

2.3 Local barrier coverage

Motivated by the observation that intruders are highly likely to follow a shorter path rather than a longer path as shown in Fig. 4(a), the concept of local barrier coverage was proposed by Chen et al. [17]. A belt region is said to be L-local k-barrier covered if every L-zone in the region is k-barrier covered, where L is a positive number and k is a positive integer. L-local k-barrier coverage guarantees that all movements whose trajectories are confined to a slice with length L of the belt region must be detected.

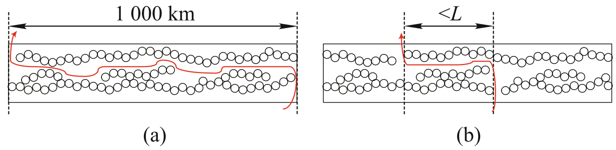


Fig. 4 Local barrier coverage. (a) Impossible path; (b) L-local barrier

How to determine whether a sensor network provides L-local barrier coverage is a nontrivial question, since there are infinite bounding boxes with length of L. Chen et al. [17] have shown the sufficient condition to achieve L-local k-barrier coverage. Furthermore, they proposed a convenient method with discretization, such that one only needs to check if the neighborhood of each sensor is barrier covered, instead of checking each of the bounding boxes.

3 Sensors and sensing model

There are several factors affecting the way of deployment and the performance of barrier coverage in sensor networks. One of these factors that must be considered is the capabilities of the sensors used. Besides, the choice of sensors will be highly dependent on the particular purpose and the application. In this section, we introduce several real-world sensors used in barrier coverage, and systematically present the sensing models of barrier coverage sensors.

3.1 Sensors

3.1.1 Underground sensors

Underground sensors are devices deployed completely below ground. Each device contains some dedicated sensors (e.g., pressure, acoustic, and magnetic), memory, a processor, a radio, an antenna, and a power source. They can be used to monitor the aboveground presence and movement of people or objects. Wireless underground sensor networks (WUSNs) are useful for home and commercial security, where sensors could be deployed underground around the perimeter of a building in order to detect intruders. WUSNs can also be used for border patrol, i.e., wireless pressure sensors are deployed along the border, and can alert the authority of illegal crossings [18]. Since the sensor's deployment is stealthy, intruders would not be likely to know about the exact positions of the sensors.

3.1.2 Ground sensors

Unattended ground sensors (UGSs) have been intensively used for military intelligence surveillance and reconnaissance applications, such as the United States Army's Future Combat Systems Program. UGS systems incoperate detectors, such as seismic detectors (geophones), magnetic detectors, acoustic sensors, etc. The detectors correlate incoming signals with pre-stored target profiles, and trigger an alarm once there is a match[2)]. For instance, UGSs can detect moving heavy vehicles (such as tanks) at a distance of 500m, as well as walking human beings from 50m[3)].

3.1.3 Infrared sensors and thermographic cameras

An infrared (IR) sensor is an electronic device that can measure the heat of an object, as well as detect motion of its surroundings through emitting and/or detecting infrared radiation. There are several types of infrared sensors, such as passive infrared sensors (PIR), infrared motion detectors, and reflective IR sensors.

Thermographic cameras can detect radiation in the infrared range of the electromagnetic spectrum and produce visual images, called thermograms. Since thermographic camera makes it possible to see one's environment with or without visible illumination day and night, it is particularly useful for military and other users of surveillance cameras.

3.1.4 Ultrasound sensors

Ultrasonic sensors generate high frequency sound waves and evaluate the echo received back at the sensor. Through calculating the time interval between sending the signal and receiving the echo, the ultrasonic sensors can determine the distance to an object. Ultrasonic sensors are often used on robots to build the region map, detect and avoid obstacles, and to navigate in the field. There are several ultrasonic sensors with different sensing capabilities, which can be found in Ref. [19].

3.1.5 Radar

Radar sensors work in an active way. They keep on transmitting radio waves and collecting radio frequency energy scattered by objects in the environment. Ultra-wideband (UWB) radars have even larger sensing ranges than either infrared or magnetic sensors. With the emergence of cheap and compact radar devices, it is becoming feasible to deploy a network of radar sensors working in concert [20].

3.1.6 Video camera

Video sensors collect visual information from the physical

2) Unattended ground sensors. http://defense-update.com/features/du-1-06/feature-ugs.htm
3) Elta systems, unattended ground sensors network(usgn). http://defense-update.com/newscast/0608/news/news1506 ugs.htm

environment to monitor the region of interest. Using video monitors and night vision scopes can achieve high accuracy in detecting human beings, and can significantly lower false alarm rates [21].

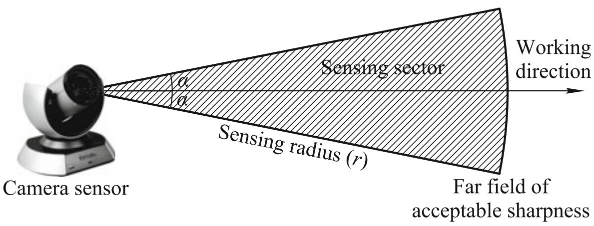


Fig. 5 Camera sensing model

3.1.7 Mobile sensors

A number of mobile sensors appeared in recent decade, including Packbot [22], Robomote [23], Khepera[4], etc. People are increasingly interested in mobile sensors for barrier coverage and intruder detection.

Unmanned aerial vehicles (UAVs) for aerial surveillance have recently been used to automatically detect and track illegal border crossing [24]. Given the large coverage and high mobility of the UAVs, the involvement of human beings in the surveillance activities can be reduced.

3.2 Sensing model

In this section, we present the sensing model for barrier coverage sensors.

3.2.1 Sensing direction

We can divide sensors into two categories according to the sensing range.

- **Omnidirectional sensors** (e.g., seismic senors): Usually, a disc with radius r is used to model the sensing range of a omnidirectional sensor. The sensing disk of a sensor located at location $\mathbf{P}$ is denoted by $D_r(\mathbf{P})$.
- **Directional sensors** (e.g., video sensors, infrared sensors, and ultrasound sensors): Each sensor $\mathbf{s}$ has a sensing radius r, a field-of-view (FoV) angle $\varphi = 2\alpha$, and a working direction $\overrightarrow{f}$. These parameters together with the position $\mathbf{P}$ of sensor $\mathbf{s}$ define the sensing sector $\mathcal{S}(\mathbf{s})$ by a 4-tuple $(\mathbf{P}, r, \overrightarrow{f}, \alpha)$ as shown in Fig. 6. For any two vectors $\overrightarrow{u}$ and $\overrightarrow{v}$, let $\angle(\overrightarrow{u}, \overrightarrow{v})$ denote the angle between them, which ranges from 0 to π. A point $\mathbf{x}$ is covered by a sensor $\mathbf{s}$ if it is in the sensing radius, i.e., $||\mathbf{Px}|| \leqslant r$, and angle of view $\angle(\overrightarrow{f}, \overrightarrow{\mathbf{Px}}) \leqslant \alpha$, where $\overrightarrow{\mathbf{Px}}$ denotes the vector from sensor $\mathbf{s}$ to point $\mathbf{x}$ as shown in Fig. 6.

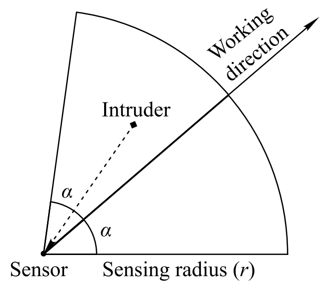


Fig. 6 Directional sensing model

Some directional sensors such as cameras have the capability of pan tilt zoom (PTZ) [25], which means that it can change its sensing direction in three dimensions and the monitored scene plane is modeled as the projecting quadrilateral area constrained by the field-of-view (FoV). Similarly, the three-dimensional directional sensing capability is denoted by a 5-tuple $(\mathbf{P}, r, \overrightarrow{f}, \alpha, \beta)$, where 2β is the vertical FoV angle.

3.2.2 Coverage model

Sensing coverage models represent the sensing capability and quality. In most cases, a sensor coverage model can be formulated as a function of the Euclidean distance (and the angle) between a space point and a sensor. We next illustrate some commonly used coverage models in the following.

Boolean sensing model is most commonly used in barrier coverage because of its simplicity. In this model, it is assumed that each sensor has a certain sensing range (e.g., disk and sector). A sensor can only detect intruders within its sensing area. Therefore, a location is covered if it lies within a sensor's sensing area.

Considering the uncertainty of the signal detection process, the boolean sensing model does not well depict the real-world scenarios. Hence, probabilistic sensing models, which assume that the detection probability is a continually decreasing function of distance, have been adopted in the literature.

As an extension to the boolean sensing model, Elfes sensing model was introduced in Ref. [26]. The probability that a sensor detects an event at a distance of d is given as follows.

$$p(d) = \begin{cases} 1, & d \leqslant r_{\min}; \\ e^{-\lambda(d-r_{\min})^{\gamma}}, & r_{\min} < d < r_{\max}; \\ 0, & d \geqslant r_{\max}, \end{cases}$$

where $r_{\min}$ is the starting distance of uncertainty and $r_{\max}$ is the maximum sensing radius of the sensor, and parameters λ and γ are adjusted according to the physical properties of the

[4] Khepera robots. http://www.k-team.com

sensor. We note that when $r_{\min} = r_{\max}$, this model degenerates to the boolean sensing model.

The dependency of factors (obstacles such as building and foliage) has been taken into account in Shadow-fading sensing model [26]. Here, the sensing ability of a sensor is not uniform in all the directions, which is similar to shadowing in radio wave propagation. If log-normal shadowing path loss model is considered, the probability that an event at a distance of d from the sensor can be detected is

$$P_{det}(d) = Q\left(\frac{10n\log_{10}\frac{d}{r_s}}{\sigma}\right),$$

where $Q(d) = \frac{1}{\sqrt{2\pi}}\int_d^{\infty} e^{-\frac{y^2}{2}}\mathrm{d}y$.

3.2.3 Deployment

The quality of coverage is closely related to the sensor deployment strategy. In certain applications, sensors may be manually placed in desired locations, and thus barrier coverage can be achieved using a minimum number of sensors, which is one of the popular topics studied in the literature. For a given rectangle or ring belt, the number of sensors required to realize barrier coverage can be calculated through critical conditions as shown in Section 4. It is natural to use the line-based deployment. However, this may not always be an optimal solution. He et al. presented a condition, under which line-based deployment is suboptimal, while indicating the advantage of curve-based deployment [27].

In some other applications, sensors may have to be deployed randomly. They may be, for example, dropped by airplanes or launched by artilleries. In such cases, barrier coverage depends on the spatial distribution of locations of the sensors. In some work, sensors are capable of knowing their location information by GPS or a certain localization algorithm [28,29]. The problem of barrier coverage was studied in Ref. [30] when nodes have location errors. Wang et al. proposed a progressive method that uses exactly the same minimum number of mobile nodes derived in theory to connect any pair of nodes with a guarantee, and further proposed a fault tolerant weighted barrier graph and proved that the minimum number of mobile nodes needed to form barrier coverage with a guarantee is the length of the shortest path on the graph.

Sensors are assumed to be deployed randomly with Poisson distribution of rate λ in Ref. [3]. A sensor network, whose sensors are distributed with Poisson distribution of rate λ and each sensor has a sensing radius of r, is denoted by $N(\lambda, r)$. If each sensor in a sensor network $N(\lambda, r)$ sleeps according to the randomized independent sleeping (RIS) scheme [31] (i.e., each sensor is active with probability p), then the sensor network is denoted by $N(\lambda, p, r)$.

In order to reduce the number of sensors needed for guaranteeing barrier coverage, multi-round sensor deployment was proposed [32]. It splits the process of sensor deployment into multiple rounds in order to solve the problem of placement errors. However, this may incur a higher deployment cost. An interesting observation is that the optimal two-round sensor deployment strategy yields the same barrier coverage performance as those with more than two rounds [32].

Two classes of multi-round deployment strategies were introduced in Ref. [33], namely fixed-density complete and fixed-density partial deployment. In the fixed-density complete deployment, sensors are deployed over the entire border in every round, while in the partial-density deployment, the deployment may be done over a part of the border in each round. The authors assumed that each sensor deployed has a fixed cost C_n and each round of deployment has a fixed cost C_r. The approaches calculate expected total cost as a function of the density of sensors in each round, and estimate the optimal density that minimizes the expected total cost.

After deployment, mobile sensors can be instructed to relocate from their initial positions to desired positions on the barrier in order to achieve better coverage. The problem therefore becomes assigning desired positions to the sensors such that the relocation cost is minimized in terms of maximum relocation distance (MinMax) [34–36], sum of relocation distances (MinSum) [37], and the number of sensors that relocate (MinNum).

However, in some situations there might not be sufficient sensors to form a barrier, for reasons such as economic consideration. In such a case, how to achieve a sub-optimal quality of barrier coverage is an interesting problem. Sensor patrolling was proposed to solve this problem, and we will go into details of this topic in Section 3.2.5.

3.2.4 Rotation

A directional sensor may be able to rotate to different working directions to monitor different sectors. Directional sensors with rotating capabilities are considered in the connected coverage problem, where a number of nodes are deployed to monitor the targets, while connectivity to the sink node needs to be maintained by well selected active nodes. Han et al. sought to select suitable sensing/relaying nodes as well as their working directions, such that the total energy cost is minimized [38].

Tao et al. studied strong barrier coverage using directional sensors with arbitrarily tunable orientations, and presented energy-efficient solutions to find directional sensors' orientations that can provide strong barrier coverage with min-sum rotation angle and min-max rotation angle [39]. When the video sensors are randomly deployed, the problem of how each sensor calculates its next new direction to obtain a better coverage was studied in Ref. [40].

The directional coverage graph was introduced by Zhang et al. [41]. Based on this model, Zhang et al. presented an integer programming formulation for the barrier coverage problem, and proposed an efficient centralized algorithm and a distributed algorithm to solve the problem.

3.2.5 Mobility

Random deployment wastes resources by placing redundant sensors, which do not contribute to the barrier formation. Moreover, in practice, it is sometimes difficult to deploy sensors manually. Recently, there has been increasing interest in deploying mobile sensors to form barrier surrounding the region automatically. Saipulla et al. first explored how to efficiently improve barrier coverage using mobile sensors with limited mobility [42].

One-dimensional motion was considered in Refs. [16,35,43], where mobile sensors were supposed to be located on a line. Chen et al. studied the problem of how to find a set of destinations on the line for the initially deployed sensors, such that each point on the barrier is covered by at least one sensor and the maximum moving distance of the sensors is minimized [35]. Dynamic sensor patrolling problem were considered within one-dimensional space. The operation time can be divided into slots of equal length, and at the beginning of each time slot, mobile sensors travel in the selected direction for certain distances. Given the assumption that the arrival of intruders at a specific location is a renew process, in which the next intruder's arrival time is correlated with the current one, two sensor patrolling algorithms [36] were proposed to maximize average intruder detection probability and minimize the average sensor moving distance.

Two-dimensional motion model was used in Ref. [43–46]. Distributed algorithms were proposed to find desired positions for sensors, so that the entire barrier is covered, when sensors can move along the barrier from their initially located positions [43]. Bar-Noy et al. [44] studied the problem of coverage lifetime maximization with limited battery powers on mobile sensors. Saipulla et al. studied the barrier coverage with a line-based sensor deployment strategy, and exploited sensor mobility to improve the performance [45]. The asymptotic full view coverage in both the static and mobile random deployed camera sensor networks was analyzed in Ref. [46], and equivalent sensing radius (ESR) is derived for full view coverage under static model, 2-dimensional random walk mobility model, 1-dimensional random walk mobility model, and random rotating model.

3.2.6 Sleep and wakeup

Typical wireless sensors are powered by conventional batteries, and thus are energy constraint. Therefore, it is important to carefully schedule sensors' sleep/wakeup modes, such that there are enough active sensors to cover the barrier at any point of time, and the lifetime of the network is maximized.

Randomized independent sleeping (RIS) scheme [47] divides time into intervals, and sets the probability of each sensor to be active as p in each interval. With this scheme, the network will last $1/p$-times the lifetime of an individual sensor. If the number of sensors to be deployed is chosen using critical conditions for weak k-barrier coverage[5)], then the RIS scheme can increase the network lifetime by the desired factor $1/p$, while guaranteeing the continuous weak k-barrier coverage of the region with high probability [3].

Compared with RIS, a localized sleep-wakeup algorithm for barrier coverage, called localized barrier coverage protocol (LBCP) [17], was proposed to prolong the network lifetime by up to 6 times. The authors also showed that LBCP provides close to optimal performance in network lifetime, while providing global barrier coverage most of the time for thin belt regions. However, this localized algorithm only provides barrier coverage for slices of bounded length and it does not protect the network against intruders that can move beyond the range of a slice.

Yamamoto et al. proposed two network construction in border security systems, sleep scheduling barrier coverage (SSBC) and security level-based SSBC (SL-SSBC) [48], which reduce about 23% and 27% of power consumption in comparison with the conventional method and SSBC, respectively. SL-SSBC also reduces non-detect time and extends operating time of the system by the tradeoff of the coverage rate.

Optimal solutions were proposed to the sleep-wakeup problems for the model of barrier coverage for both the homogeneous and heterogeneous lifetime cases [49]. However, the proposed optimal solutions have a security problem that

5) Please refer to the critical conditions in Section 4.1.1

the breach appears when one barrier-cover of sensors is replaced by another barrier-cover crossing with it. That means an intruder may trespass into the protected area by the alternating barrier-covers by identifying a set of points called barrier-breaches. Consequently, two remedies of this problem were proposed in Ref. [50].

4 Barrier coverage algorithms

In this section, we present recent developments in this field, and give a taxonomy of these literatures. The barrier coverage problem could be classified into various categories according to different criteria, which are listed as follows.

- Sensor mobility According to the mobility of sensors, the barrier coverage problem may focus on stationary sensors, mobile sensors and a mixture of them.
- Sensing range The sensing range of sensors may be omnidirectional or directional, and leads to different solutions to the barrier coverage problem.
- Coverage model Different coverage models are used in barrier coverage, such as boolean sensing, probable sensing and full-view sensing, etc.
- Problem type The problem on barrier coverage mainly contains critical condition analysis, coverage detection, sensor deployment and related optimization problems.

In the rest of this section, we give a survey of recent developments on barrier coverage problem, according to the types of sensor networks.

4.1 Barrier coverage with stationary sensors

4.1.1 Critical condition analysis

The critical conditions for weak k-barrier coverage and strong k-barrier coverage with omnidirectional sensors were discussed in [3] and [4], respectively.

• **Critical conditions for weak k-barrier coverage**

Theorem 2 establishes a sufficient condition for the k-coverage w.h.p. of all orthogonal crossing lines in the protected region.

Theorem 2 (Sufficient condition for weak-coverage [3]) Let $N(n, p, r)$ be a Poisson distributed sensor network over a belt region $\mathcal{B}_s$ of dimension $(\lambda_1, \lambda_2, \frac{1}{s})$. If the following inequality is satisfied for sufficiently large s, then all the orthogonal crossing lines in the region are k-covered w.h.p. as $s \to \infty$.

$$c(s) = \frac{2npr}{s\log(np)} \geqslant 1 + \frac{\phi(np) + (k-1)\log\log(np)}{\log(np)}.$$

• **Critical conditions for strong k-barrier coverage**

Liu et al. showed that the existence and strength of strong barrier coverage with omnidirectional sensors depend on the width-to-length ratio of the strip region [4]. The critical conditions for strong k-barrier coverage in the rectangular belt are given as the following theorem.

Theorem 3 (Critical conditions for strong k-barrier coverage [4]) Let $N(\lambda, p, r)$ be a Poisson distributed sensor network over a rectangular belt region $\mathcal{B}_s$ of dimension $(s, s, 1/s)$. There exists $\theta > 0$, if $\lambda = \theta(s\log s)^2$ and the radius $r = \frac{1}{s\log s}$, the strip is strongly barrier covered as $s \to \infty$.

The problem of how to construct strong barriers was studied in Ref. [4]. An efficient distributed algorithm was devised to construct disjoint barriers in a large sensor network to cover long boundary areas of irregular shapes.

However, the critical conditions for directional sensors have not been well studied. The k-barrier coverage problems in wireless visual sensor networks (WVSNs) were considered in [51], to maximize the number of distinct defense curves with as few camera sensors as possible.

4.1.2 Quality of barrier coverage

Based on the concept of L-local k-barrier coverage as mention in Section 2.3, the concept of quality of a sensor deployment for barrier coverage was introduced in [52]. The definition is given as follows.

Definition 4 (Quality of k-barrier coverage [52]) The quality of a sensor deployment for k-barrier coverage, denoted by Q_k, is defined to be the maximum L such that the belt is L-local k-barrier covered; i.e., $Q_k = \max\{L :$ the belt is L-local k-barrier covered$\}$. If there is no such L (i.e., if the belt is not even 0-local k-barrier covered), then define $Q_k = -1$.

Chen et al. [52] proposed an algorithm that identifies all local zones that need to be repaired, if the measured quality is less than a desired value. Their proposed algorithm can be extended to a distributed one, which measures the quality of k-barrier coverage and identifies regions to repair. Possible approaches to actually repair a zone are also discussed.

Based on the maximal support path and the maximal breach path as mentioned in Section 2.2.1, two new coverage measures, the support and breach of a sensor network, were defined for sensor networks by Lee et al. [53]. They also gave an algorithm to compute the value of the support/breach of a given sensor network, and proposed a new algorithm for finding positions to deploy new sensors to improve the value of the coverage measure with a guaranteed performance.

4.1.3 Directional sensors

Tao et al. investigated the problem of finding appropriate orientations of directional sensors such that strong barrier coverage can be provided [54]. By exploiting geographical relations among directional sensors and deployment region boundaries, the concept of virtual node is introduced to reduce the solution space from a continuous domain to a discrete domain. By constructing a directional barrier graph (DBG), it can be determined whether there are directional sensors' orientations that can provide strong barrier coverage over a given belt region.

4.1.4 Full-view coverage

In contrast to traditional scalar sensors, camera sensors can provide much richer information about the monitored regions with images and videos. However, the costs of camera sensors are normally much higher than the scalar sensors. Moreover, the video monitors require the target within the line of sight, and the miss rate increases when the monitoring area encounters obstacles, such as rocks, brushwood, and trees. What's more, a fundamental difference between camera and scalar sensor is that camera sensors may generate very different views of the same object, if they are from different viewpoints. As a result, it is not sufficient to form a camera barrier by only considering the sensing ranges of the cameras. Research outcomes from computer vision show that the subject is more likely to be recognized by the recognition system, if the picture is captured at or near the frontal viewpoint.

Wang et al. proposed a novel model called full-view coverage [55], and studied how to form a full-view coverage.

Definition 5 (Full-view coverage [55]) As shown in Fig. 7, a point $\mathbf{x}$ is full-view covered if for any facing direction (i.e., any vector $\overrightarrow{d}$), there is a sensor s whose the sensing sector $\mathcal{S}(\mathbf{s}) = (\mathbf{P}, r, \overrightarrow{f}, \alpha)$, such that $\mathbf{x}$ is covered by s and $\angle(\overrightarrow{d}, \overrightarrow{\mathbf{xP}}) < \theta$, where $\theta \in [0, \frac{\pi}{2}]$ is a predefined parameter which is called the effective angle (EA). A region is full-view covered if every point in it is full-view covered.

The problem of constructing a camera barrier in both random and deterministic deployments was studied by Wang and Cao [56]. They presented an elegant method to select camera sensors from an arbitrary deployment in order to form a camera barrier. They also presented algorithms to deploy minimized number of camera sensors to form a barrier coverage in a deterministic way.

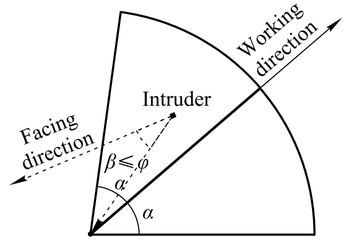


Fig. 7 Full-view coverage

Based on the full-view coverage model, Ma et al. studied the minimum camera barrier coverage problem (MCBCP) in wireless camera sensor networks [57]. They divided the target area into a number of disjoint full-view-covered (FVC) regions and non-full-view-covered (NFVC) regions, and used a weighted directed graph to model the FVC regions and their connections. The two boundaries are represented as source and destination in the graph. The weight on an edge denotes the cost of connecting two FVC regions. It can be shown that any path from the source to the destination in the weighted directed graph is a camera barrier, and the path with the minimum cost is the optimal one.

Yang et al. [58] introduced a novel view-coverage model to support the need of face recognition. Based on the model, they proposed a distributed multi-round view-coverage enhancing algorithm to make the camera sensors coverage to a stable state, in which the amount of overlapping view-coverage is minimized.

Yu et al. [59] proposed local face-view barrier coverage, which guarantees statistical barrier coverage in camera sensor networks. A rigorous probability bound for intruder detection is derived under a feasible deployment pattern.

4.1.5 Radar coverage

Radar sensors are becoming more and more feasible, considering the emergence of cheap and compact radar devices. The major obstacle of applying radar sensors is the hardness of distinguishing scattered signals between objects that are not of interest as well as objects of interest (e.g., intruder).

One method to combat the effect of clutter is to utilize the Doppler frequency shift extracted from the echo signal due to the relative motion of a target with respect to the radar. The concept of Doppler coverage for a network of spatially distributed radars was discussed in [60], and an algorithm was designed to derive the minimum sensor density required for the entire region to be D-covered.

Definition 6 (Doppler coverage [60]) A point **x** is Doppler-covered by a sensor s located at point **P** if **x** is covered by s and for any facing direction $\overrightarrow{d}$ from **x**, $\angle(\overrightarrow{d}, \overrightarrow{\mathbf{xP}}) < \theta$ or $\pi - \theta < \angle(\overrightarrow{d}, \overrightarrow{\mathbf{xP}}) < \pi$, where $\theta \in [0, \frac{\pi}{2}]$ is a predefined parameter which is called the effective Doppler angle. A region is Doppler covered if any direction from **x** is Doppler-covered by some sensor.

Due to the flexibility in deploying the radar transmitter and receiver separately, bistatic radars are more favorable than monostatic radars for barrier coverage. Bistatic radar networks (BRNs) were introduced for intrusion detection by Gong et al. [61]. They studied the problem of where should the BRs be placed to achieve the optimal coverage quality. They showed that the shortest barrier-based placement is not optimal in general, and it is optimal if the shortest barrier is also the shortest line segment connecting the region's two boundaries. Focusing on characterizing the optimal placement of the BRs on a line barrier, the authors reformulated the problem as finding the optimal placement order with the optimal placement spacing of the BR node, and proposed an optimal solution.

4.1.6 Probabilistic barrier coverage

In some scenarios, it is good enough to achieve barrier coverage with high probability, and that would significantly reduce the number of sensors deployed.

Noori et al. [62] used geometric probability to determine the probabilities, including full path coverage, distribution of the number of uncovered gaps over the path, and the probability of having no uncovered gaps larger than a specific size. Based on their results on the probability of full path coverage, a tight upper bound was derived for the number of nodes guaranteeing the full path coverage with a desired reliability.

Li et al. [63] studied the problem of how many sensor nodes should be deployed to achieve weak k-barrier coverage with a given probability. A lower bound for the probability of weak k-barrier coverage with and without considering the border effect was derived, respectively.

Based on the probabilistic sensing model as mentioned in Section 3.2.2, the detection probability of arbitrary path across the barrier of sensors can be defined and analyzed theoretically. Taking the maximum speed of possible intruders into consideration, Li et al. [64] considered the problem of minimum weight ϵ-barrier, which is to choose a minimum weight barrier that can provide ϵ-barrier coverage against the possible intruders with a maximum speed. Here, ϵ is a threshold set by the application. They proved that the minimum weight ϵ-barrier problem is NP-hard, and proposed a bounded approximation algorithm, called Minimum Weight Barrier Algorithm, to schedule the activations of the sensors.

The efficient sensor deployment problem and energy-efficient barrier coverage problem for directional sensor networks were addressed by Zhao et al. [65]. They described a deployment model for the distribution of sensor locations to analyze whether a target area can be barrier covered.

4.2 Barrier coverage with mobile sensors

As shown in Section 3.2.5, mobile sensors are introduced to efficiently improve barrier coverage and to reduce the necessary number of sensors deployed. A fully distributed algorithm based on virtual force and convex analysis was developed for the objective to relocate the sensors from the original positions to form a strong k-barrier coverage for the RoI [66].

The problem of achieving strong k-barrier coverage with the minimum energy consumption in mobile sensor network was studied in Ref. [67]. Ban et al. formulated the problem of 1-Barrier Coverage of Minimum Energy consumption, and proved its NP-hardness. They proposed an approximation algorithm, namely Constructing Baseline Grid Barrier, to construct 1-barrier coverage. Furthermore, they presented a divide-and-conquer algorithm to achieve strong k-barrier coverage for large sensor networks.

Bhattacharya et al. [68] considered the problem of minimizing the total moving distance of n sensors to the perimeter of the given circle, such that the new positions of sensors form a regular n-gon (a regular polygon with n sides), and proposed an algorithm with a time bound of $O(n^{3.5} \log n)$. Later, Tan and Wu improved the algorithm with an $O(n^{2.5} \log n)$ time complexity.

Saipulla et al. [42] first explored the fundamental limits of sensor mobility on barrier coverage. They showed that when a total number of m mobile sensors are deployed in a rectangular area of dimension $l \times w$ and all the sensors have the same sensing range of r, a maximum number of $\lfloor \frac{2mr}{j} \rfloor$ barriers can be formed, and the minimum of the maximum (minimax) moving distance between all sensors is $\Theta(\sqrt{lr} + w)$ w.h.p.. An efficient sensor mobility scheme that achieves the maximum barrier coverage and minimizes the maximum sensor moving distance was proposed.

The intrusion detection problem in mobile sensor networks (MSNs) was demonstrated to be similar to the classical kinetic theory of gas molecules in physics [69].

A distributed and asynchronous algorithm MobiBar was introduced for sensors autonomously coordinating their movements in order to achieve a final stable deployment with the highest level of barrier coverage [70]. MobiBar terminates in finite time achiving that the final deployment provides the maximum level of barrier coverage with the available sensors. MobiBar was also proved to be selfheal even after several sensor faults have compromised the coverage provided by the network.

When there are not sufficient sensors to form a single barrier, i.e., m mobile sensors are needed to guarantee full barrier coverage, but only n ($n < m$) mobile sensors are available, the problem of achieving barrier coverage in sensor scarcity case by dynamic sensor patrolling was studied by He et al. [16,71]. They proposed two sensor patrolling algorithms, i.e., periodical monitoring scheduling and coordinated sensor patrolling to achieve barrier coverage in the case of sensor scarcity.

Gu et al. [35] studied the problem of minimizing the total moving distance of n sensors on a line to form a barrier coverage of a specified segment of the line. Hesari et al. [43] proposed distributed algorithms to find final positions for sensors so that the entire barrier is covered, given that the sensors are initially located at arbitrary positions on the barrier. Bar-Noy et al. [44] studied the problem of maximizing the coverage lifetime of a barrier by mobile sensors with limited battery powers. The barrier coverage of a line-based sensor deployment strategy and how to exploit sensor mobility to improve barrier coverage are studied by Saipulla et al. [45].

The barrier coverage problem for hybrid directional sensor networks was studied in Ref. [72]. By introducing the notion of directional barrier graph, the authors proved that the minimum number of mobile sensors required to form a barrier is the length of the shortest path from the source node to the destination node on the graph. The problem of minimizing the total moving cost of mobile sensors to form a barrier was formulated as the minimum cost bipartite assignment problem, which can be solved in polynomial time by the Hungarian algorithm. They further extended the solution to k-barrier coverage formation in Ref. [73] and fault tolerant barrier coverage formation when sensors have location errors [30].

Combined with full-view coverage mentioned in Section 4.1.4, the asymptotic full view coverage in both the static and mobile random deployed camera sensor networks was analyzed in [46]. Equivalent sensing radius were derived for full view coverage under static model, 2-dimensional random walk mobility model, 1-dimensional random walk mobility model, and random rotating model.

4.3 Optimization

In barrier coverage, several optimization problems were studied.

Lai et al. formulated the optimal (k, p, t)-barrier coverage problem to construct sink-connected barrier for WSNs to achieve three goals [74]: 1) maximizing the degree k of barrier coverage, 2) maximizing the probability p of detecting intruders crossing the RoI, and 3) minimizing the expected transmission time t to send sensed data from detecting nodes to sink nodes.

The problem of building sensor barriers with minimum cost in wireless sensor networks was considered in Ref. [75], where the cost can be any performance measurement and normally is defined as the resource consumed or occupied by the sensor barriers. A distributed PUSH-PULL-IMPROVE algorithm was presented to solve this problem in Ref. [75].

Ma et al. [76] studied two complementary problems of k-barrier coverage, including the minimum energy cost k-barrier coverage problem in static wireless sensor networks and the maximum k-barrier coverage problem in limited mobile wireless sensor networks.

Fan et al. [77] investigated the coverage of a line interval with a set of wireless sensors with adjustable coverage ranges. They designed polynomial-time optimal and approximation algorithms to minimize cost for discrete variant and continuous variant of the problem, respectively.

4.4 Summary

We classified the prior work into two categories, barrier coverage with stationary sensors and with mobile sensors.

When we cover a barrier with stationary sensors, the critical conditions and quality of barrier coverage are well studied. If we use directional sensors, a directional barrier graph (DBG) is usually used to determine whether strong barrier coverage over a belt region exists. Some special barrier coverage problems, such as full-view coverage, radar coverage, and probabilistic barrier coverage, are also discussed.

Mobile sensors were introduced to efficiently improve barrier coverage and to reduce the necessary number of sensors deployed. Several optimization problems were studied to maximize the quality of barrier coverage or minimize the cost of barrier coverage.

Based on the discussions in this section, the key features of aforementioned literature are summarized in Table 1.

Table 1 Summary of works on barrier coverage

Reference	RoI	Sensor mobility		Sensing range		Sensing model	Problem type
		Static	Mobile	Disk	Sector		
[3]	Belt	✓		✓		Boolean	k-barrier testing and deployment
[4]	Belt	✓		✓		Boolean	Barrier deployment
[17]	Open belt	✓		✓		Boolean	Barrier deployment
[52]	Open belt	✓		✓		Boolean	Quality of barrier coverage, k-barrier coverage
[27]	Curve	✓		✓		Boolean	Sufficient condition analysis
[61]	Belt	✓		✓		SNR	Barrier deployment
[34–36,78]	Open belt	✓		✓		Boolean	Sensor scheduling
[37,78]	Open belt	✓		✓		Boolean	Sensor scheduling
[39,54]	Open belt	✓			✓	Boolean	Strong barrier coverage
[51]	Open belt	✓			✓	Boolean	k-barrier coverage
[40]	Open belt	✓			✓	Boolean	Sensor scheduling
[55]	Belt	✓			✓	Full-view	Full-view barrier detection
[56]	Belt	✓			✓	Full-view	Full-view barrier detection and deployment
[57]	Belt	✓			✓	Full-view	Minimum camera barrier coverage
[58,59]	Belt	✓			✓	Full-view	Face recognition coverage
[60]	Belt	✓			✓	Doppler	Barrier deployment
[41]	Belt	✓			✓	Boolean	Strong barrier deployment
[7]	Open belt	✓		✓		Boolean	Barrier detection
[32,33]	Open belt	✓		✓		Boolean	Barrier deployment
[8]	Open belt	✓		✓		Boolean	Strong 3-dimensional barrier
[11,12]	Open Belt	✓		✓		Probability	Probabilistic barrier coverage
[48–50]	Open belt	✓		✓		Boolean	Sleep scheduling
[13]	Open belt	✓		✓		Boolean	One-way barrier coverage
[79]	Open belt	✓		✓		Probability	Energy-efficient target detection
[30]	Belt	✓		✓		Boolean	Barrier deployment
[80]	Open belt	✓		✓		Probability	Probabilistic trap coverage
[69]	Open belt	✓		✓		Boolean	Dynamic k-barrier coverage
[67]	Open belt		✓	✓		Boolean	Strong k-barrier coverage
[42,68,81]	Open belt		✓	✓		Boolean	Barrier coverage improvement
[70]	Open belt		✓	✓		Boolean	Barrier deployment
[16,71]	Open belt		✓	✓		Boolean	Dynamic sensor patrolling
[9]	Open belt		✓	✓		Boolean	Dynamic sensor patrolling
[43]	Open belt		✓	✓		Boolean	Barrier deployment
[44]	Open belt		✓	✓		Boolean	Maximizing barrier coverage lifetime
[45]	Open belt		✓	✓		Boolean	Barrier deployment
[64]	Belt	✓	✓	✓		Probability	Minimum weight ϵ-barrier coverage
[72,73]	Belt		✓		✓	Boolean	Barrier formation
[46]	Open belt	✓	✓		✓	Boolean	Full-view coverage

5 Open issues

In this section, we present selected open research issues that still need to be addressed.

5.1 Sensor with rotating capabilities

In directional sensing models, a sensor can only sense in the direction of its orientation. A rotating directional sensor can change the orientation of its sensor at a certain rotational speed to provide good coverage. When these sensors are randomly deployed in the RoI, one interesting problem is how to select appropriate rotating directional sensors and their working orientations to guarantee barrier coverage.

5.2 Non-line deployment

As shown in Section 4, most of existing work focused on line-based deployment, which can reduce the problem dimension and facilitate analysis. However, realistic environments are much more complicated and the barrier might not be a line as we wish, e.g., the mountain area. Finding the optimal deployment curve is highly non-trivial given an arbitrary deployment region. It is still an open problem how to deploy sensors on the optimal curve.

5.3 Three-dimensional barrier coverage

Most existing researches focused on the problem of barrier coverage in two-dimensional spaces. However, sensors deployed in the atmosphere, the sea, and the outer space may need to guarantee the barrier covered in three-dimensional space, or referred to shell coverage. It is not straightforward to extend the approaches proposed for two-dimensional barrier coverage to adapt to three-dimensional barrier coverage, and new algorithms need to be designed.

5.4 Barrier coverage with heterogeneous sensors

In practice, we may need heterogeneous sensors to deal with the problem of barrier coverage, since the sensors may come from different manufacturers and thus have different sensing characteristics. Furthermore, it is possible to take the advantages of various kinds of sensors to form a hybrid barrier, in order to improve the quality of coverage and/or reduce the deployment cost. It is interesting to consider the problem of barrier coverage with heterogeneous sensors.

6 Conclusion

Barrier coverage, which guarantees that every movement crossing a barrier of sensors will be detected, is one of the most important issues for critical sensor network applications such as national border control and disaster warning. In this survey, we have reviewed real-world sensors used for barrier coverage in terms of physical metrics, and discussed several principal issues in the modeling of barrier coverage. Several barrier coverage problems in different scenarios, including local barrier coverage, full-view coverage, Doppler coverage, and dynamic barrier coverage have been discussed. In the end, we have pointed out open research issues that still need to be addressed.

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