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Deploy Efficiency Driven k-Barrier Construction Scheme Based on Target Circle in Directional Sensor Network

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Abstract With the increasing demand for security, building strong barrier coverage in directional sensor networks is important for effectively detecting un-authorized intrusions. In this paper, we propose an efficient scheme to form the strong barrier coverage by adding the mobile nodes one by one into the barrier. We first present the concept of target circle which determines the appropriate residence region and working direction of any candidate node to be added. Then we select the optimal relay sensor to be added into the current barrier based on its input-output ratio (barrier weight) which reflects the extension of barrier coverage. This strategy looses the demand of minimal required sensor nodes (maximal gain of each sensor) or maximal lifetime of one single barrier, leading to an augmentation of sensors to be used. Numerical simulation results show that, compared with the available schemes, the proposed method significantly reduces the minimal deploy density required to establish k-barrier, and increases the total service lifetime with a high deploy efficiency.

Keywords directional sensor network, barrier coverage, target circle, deploy efficiency

1 Introduction

Due to the increasing demand for security, applications like intrusion detection and border surveillance (referred to as barrier coverage) become a fundamental problem in wireless sensor networks (WSNs), attracting considerable research concern [1, 2]. In these applications, it is not necessary to cover every point of a region; these applications only need to detect intruders that cross the region. The barrier coverage problem was first studied based on the isotopic sensing model [3, 4], where an intruder is fully detected if its distance to the sensor is less than its sensing range. In real applications, sensors typically have limited angle of view, such as infrared sensors, camera sensors, which are termed as directional sensors. A network composed of directional sensors is called a directional sensor network (DSN). Barrier coverage in DSN has attracted increasing interest [5–10] due to the wide application range of barrier coverage and unsolved issues related to constraint energy storage, deploy efficiency, etc.

To effectively detect intrusions from any path, strong barriers are needed. Two types of barrier coverage: strong barrier coverage and weak barrier coverage, were also introduced in [5]. Strong barrier coverage needs to detect intruders with arbitrary moving paths while weak barrier coverage only needs to detect intruders moving along congruent crossing paths. Existing strategies used to create strong barrier coverage services with stationary sensors demand a huge number of sensors to be deployed [11–13], resulting in high hardware cost. Due to the inevitable heterogeneous nature of the sensors' battery storage, the lifetime of a barrier is fully

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determined by the one with minimum residual energy. Once it fails, all sensors in the barrier can hardly be reused.

Concerning the drawbacks of stationary sensors and the advances of technology[14], sensors with rotation ability were extensively studied in [13, 15, 16]. Some authors even considered using mobile sensors to construct barriers, or to fill the gaps that cannot be repaired merely by rotation[17–19]. However, to the best of our knowledge, there is no well acknowledged method guiding barrier construction with mobile sensors, despite that several exploitations have been done[20, 21].

In real applications, barriers are typically constructed in distributed manner, in order to provide unlimited coverage length with respect to sensors' communication range. Under this scheme, a relay sensor adjusts its position and orientation to have its field of view (FoV) overlapped with that of the ancestor node. These procedures continue until the FoV of the terminal sensor reaches the boundary. Determining the target position of the relay sensor and the intersection point of the FoVs is of crucial importance, as it is directly related to the barrier quality and the deploy efficiency.

The barrier's lifetime and the number of sensors required are two frequently used criteria for evaluating constructing schemes. To this end, Cheng and Tsai proposed a rotation strategy that takes the original positions as the target of relay sensors, and selects the one that has the biggest gain as its successor[13]. This energy-orientated scheme maximizes the barrier's lifetime while excluding a large amount of sensors used. Ren *et al.* recently have proposed a gain-orientated scheme which requires each successor provide a gain as large as sensing radius r_s[20, 21], leading to minimum sensor nodes requirement.

However, both schemes have drawbacks. The energy-orientated scheme excludes sensors away from the ancestor node, leading to a great waste of the deployed sensors (low deploy efficiency). The gain-orientated strategy augments the energy expenditure on position adjusting, resulting in low barrier life expectance (low quality barrier). The preliminary results have shown that depending on the target position, barriers' lifetime varies greatly. Therefore, how to construct the barrier coverage effectively in terms of deploy efficiency and service quality is a challenging task.

To address the above-mentioned challenge, this paper proposes a distributed barrier construction scheme to efficiently build up strong directional k-barrier coverage. Its main contributions are detailed as follows.

- It speculates all possible target positions (a target circle) for the relay sensors to be located.
- It introduces the input-output ratio as a criterion to efficiently choose relay sensor.
- It proposes a barrier construction scheme that gives high service lifetime by taking use of all deployed sensors.

The rest of this paper is organized as follows. A brief review of barrier coverage in DSN is presented in Section 2. Section 3 introduces the related assumptions and definitions. Section 4 presents the theoretical reasoning and analysis. The proposed barrier construction scheme is detailed in Section 5. The performance of the proposed scheme is experimentally evaluated in Section 6, followed by concluding remarks in Section 7.

2 Related Work

In this section, we provide a short review of literatures related to coverage problems in DSNs. We start with sensor models used in WSNs, and present the work based on these models.

Designing a reasonable sensing model to accurately describe the property of a sensor is of fundamental importance in DSNs research. Different from conventional omnidirectional models, where a sensor can detect a circular area[22], directional sensors (e.g., cameras) have a limited sensing angle. Tao and Ma firstly abstracted the limited angle of view of directional sensors as a 2D-sector denoted by a 4-tuple[23]. Based on this model, a set of work has been done. They introduced the virtual potential concept to solve the area coverage problem[23]. Chen *et al.*[24] proposed a coverage-enhancing algorithm based on overlap-sense ratio. Mohamadi *et al.*[25] proposed a learning automata based algorithm to improve the quality of targets coverage.

Different from area coverage, the barrier coverage problem focuses on providing the service of detecting any intrusion that penetrates the boundary of interesting regions. Mostafaei *et al.*[26–28] firstly modeled barrier coverage problem based on stochastic coverage graph, and then used a learning automata scheme to find the best nodes to assure barrier coverage at any moment. They also proposed the imperialist competitive algorithm (ICA) to improve the service lifetime of barrier coverage in a deployed network. Wang *et al.*[29] analyzed the effects of location errors for barrier coverage and proposed a fault-tolerant weighted barrier graph to model the barrier coverage formation problem. Tian *et al.*[30] studied the concept of 2-dimension

(2D) k-barrier, and investigated establishing 2D barriers on a square region only with sensors' local neighbor information. Although these algorithms could achieve good barrier coverage with isotropic sensors, they are typically not applicable to DSNs. To fill this gap, a set of work has been done. Zhang *et al.*[31] introduced a directional coverage graph to study the Maximum Directional Sensor Barrier Problem (MDSBP). Tao *et al.*[32,33] proposed a polynomial time algorithm to achieve strong barrier coverage with a minimal number of directional sensors. Shih *et al.*[34] proposed a Cone-Based coveRage Algorithm (CoBRA) which utilizes the observation that each camera node can determine possible barrier line with its neighbors. Similarly, the basic idea of [35] was to define a strong/weak barrier pair of the sensor neighbors' position information.

These methods show great success; however redundant sensors are required. Considering the fact that DSNs can be deployed using tunable cameras, the model with rotation ability was proposed[5]. Sung and Yang[36] used the VORONOI diagram to adjust the location and working direction in order to improve the quality of field coverage. This centralized scheme requires sensors report their information to all their neighbors, limiting this scheme's application in large areas. Ssu *et al.*[11] presented a distributed scheme that commences by selecting an initial node, which is then used to activate appropriate nodes to extend the barrier toward the left and the right hand end boundaries of the sensing field. Under this scheme, barrier services can be provided without any constraints due to limited communication range. After this, improvements are made by researchers. Chang *et al.*[37] divided a network region into grids to simplify the k-barrier coverage problem and investigated two barrier construction policies: BA and BRA. Cheng and Tsai[13] proposed the D-TriBR scheme that selects the node with maximum barrier contribution only by rotation capability as the relay sensor to construct barrier coverage in the distributed manner. Tao *et al.*[15] adjusted the directional sensor's orientation with the minimum total rotation angle to create strong barrier(s).

With the advances of modern technology, sensor models with both rotational and locomotive capability were studied. Guvensan and Yavnz[38] exploited area coverage enhancement considering the capability of rotation and mobility. Wang *et al.*[17] studied how to achieve 1-barrier coverage in hybrid DSNs by moving mobile sensors to fill gaps between stationary sensors. Ma *et al.*[39] used sensors with limited mobile capability to form barriers. Ren *et al.* proposed the NS-DBC scheme[20] and DSBCSB[21] to create directional barrier coverage considering both rotation and mobility capability.

The previously mentioned models are typically called the Boolean model, as a sensor detects any targets as long as they are within this sensor's FoV and fails when targets are out of this sensor's fixed FoV. A real sensor would be more likely to detect a target that is physically closer to the sensor. Fan *et al.*[40] proposed a directional probabilistic sensing model with changing angle (DPCA), created four target locations of mobile nodes in distributed manner, and selected the one with the optimal energy efficiency ratio (EER) as the actual target location to form barriers.

Barrier lifetime is frequently used to evaluate the performance of proposed methods. Due to the limited battery capacity of wireless sensors, barrier lifetime is fully determined by sensors' residual energy after required adjustments. Two different strategies can be taken to increase barriers' lifetime: 1) reducing the energy consumption required on barrier construction; 2) duty-cycling all possible barriers existing in one deployment. The former is an energy-oriented scheme, aiming at minimizing required energy for each sensor to form the barrier, for example, selecting a sensor that provides the largest gain without any adjustment on its location as the relay sensor[13]. For the latter method, its effect is fully determined by the number of possible barriers within one deployment, i.e., the more the barriers, the longer the service and the lifetime of each barrier.

Despite of the huge amount of excellent work related to the field of increasing barrier lifetime using duty-cycling scheme[41,42], there is a research gap that takes into account not only the quantity but also the quality of barriers in a random deployment. To this end, we here propose a deploy efficiency driven barrier construction algorithm. The proposed concept target-circle enables all neighboring sensors to find an efficient way to form the barrier(s), leading to the increase of the number of barriers that can be created. Using the input-output ratio as the only criterion to select relay sensors guarantees the quality of each barrier.

3 Target Circle and Related Concepts

Unlike the omnidirectional model, directional sensors have a limited view angle and specific orientation (sensing direction). Therefore, a sector represented by a 4-tuple (S, r_s, α, β) is commonly adopted to denote the FoV of a directional sensor, where $S = (x_s, y_s)$ is the location of sensor (x_s is the x-coordinate, y_s is the y-coordinate), r_s is the sensing radius, α is the sensing angle, and β is the working direction with a value in the range of $[0,\ 2\pi)$. Clearly, the omnidirectional sensing model is a special case of the directional sensor model with $\alpha = 2\pi$.

There are two models available for describing the sensing ability: 0-1 model and probabilistic model[40]. The former detects a target if it is within the FoV of a sensor. For example, as shown in Fig.1, the target point $p(x, y)$ locates within the FoV of sensor S; thus it is detected by sensor S with full certainty. The latter gives a probabilistic description of its output.

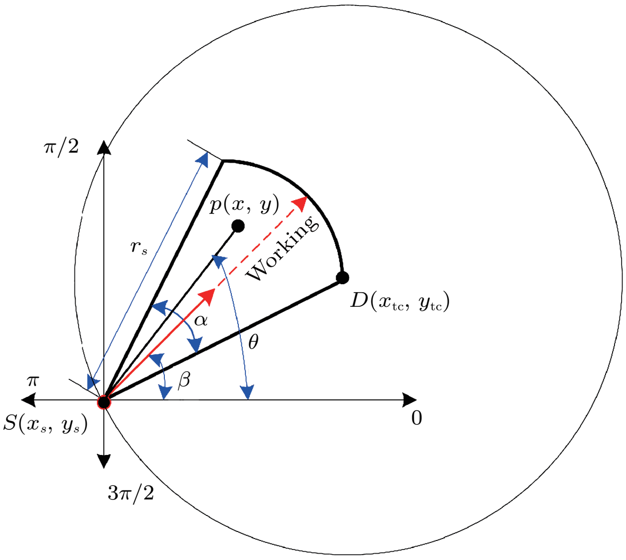


Fig.1. Directional sensing model and target circle. A directional sensor is described by a 4-tuple (S, r_s, α, β), where S is the location coordinate describing the position of the sensor. The circle of radius r_s drawn at point D (one with the largest x coordinate) in the FoV of sensor is the target circle of sensor S.

In this paper, we adopt the first sensing model, and assume that N mobile sensors are randomly deployed according to the Poisson distribution in a belt area, which forms four end boundaries: left, right, top and bottom. To facilitate the description of the proposed algorithm, some assumptions are used.

- A homogeneous network consists of mobile sensors with the same sensing radius and angle.
- A sensor is aware of its own location and working direction.
- The construction process starts from left to right.
- A sensor consumes 1.8 J for a 180°-rotation, and 3.6 J for a 1 m physical movement, i.e., $J_m = 3.6$, $J_r = 1.8$[38].

Definition 1 (Strong Directional Barrier). *In an RoI (region of interest), a strong directional barrier is a set of nodes satisfying the following criteria.*

- *There exist only one initiator and one terminator.*
- *The initiator has at least one intersection with the left end boundary. The terminator also has at least one intersection with the right end boundary.*
- *Both the initiator and the terminator are connected to only one node with an overlapped sensing region.*
- *Besides the initiator and the terminator, each node in the barrier can only be connected to two sensors: one is called its ancestor, and the other is its successor.*

An example of strong barrier is shown in [43].

Theorem 1. *Constructing a continuous barrier with a node within or on a circle of radius r_s centered at the boundary of the FoV of an ancestor requires only rotational operation.*

Proof. The distance d of any node within the circle to its center is less than r_s. Rotating the node with sensing range r_s will always form an overlapped sensing region with that of the ancestor. ☐

Theorem 1 implies: 1) nodes within the circle can form the directional barrier only by rotating the sensing direction; 2) nodes out of the circle could form the barrier by moving onto the circle and rotating. Typically, the directional barrier has a belt form. To construct a barrier along certain direction (labelled as x-axis) with minimum sensor nodes, it is reasonable to take full advantage of the ancestor's sensing capability.

Definition 2 (Target Circle). *It is a circle of radius as same as sensing range r_s centered at the point with maximal x-coordinate of a sensor's FoV.*

As shown in Fig.1, point D has the maximum x coordinate within the FoV of node S, and the circle with radius r_s drawn at this point is the target circle of ancestor node S.

During barrier construction, nodes are added to the barrier in a relay form to extend its coverage. The extension that a node brings is defined as barrier gain (l)[40]. Clearly, large barrier gain l reduces the number of nodes required to provide barrier coverage over the RoI. However, the energy expenditure E_c challenges the long-term service of the barrier due to sensors' limited battery capacity. To comprise the energy consumption and barrier gain, we introduce barrier weight w.

Definition 3 (Barrier Weight of a Node). *It is the ratio between energy expenditure E_c on its location and orientation adjustment and the resulted barrier gain l,* *i.e.*,

$$w = \frac{E_c}{l}, \tag{1}$$

where E_c is the sum of moving and rotating energy consumption. Clearly, w describes the quality of candidate sensor. Large w corresponds to low residual energy to be used to provide coverage service.

Definition 4 (Minimum Weight Barrier Problem). *Given a belt RoI and N homogeneous mobile sensors, the minimum weight barrier problem is to choose a set of sensors with minimum weights to form a directional barrier.*

To effectively address the minimum weight barrier problem, two fundamental questions should be answered. According to Definition 2, it specifies the possible region where candidate relay sensors can form the strong barrier with the ancestor. How to pinpoint the optimal position? And how to determine the sensing direction of the relay node? When the questions are answered, the required energy expenditure E_c and the resulted gain l can be calculated. We will address these two questions in Section 4. The minimum weight barrier problem is investigated in Section 5.

4 Theoretical Analyses

This section discusses how to determine the target location and orientation of candidate nodes to be added to the barrier and how to determine the weights of candidate nodes. Several symbols are defined (see Table 1) to facilitate the description. The subscripts *an*, *r* and *t* denote the ancestor, rotating and the target respectively. For example, $x_{\rm an}^{\max}$ denotes the point with maximal x coordinate within the FoV of the ancestor.

Table 1. Notations

Notation	Description
k	Barriers
L	Length of area
l	Barrier gain
x_L	x coordinate of the left border of area
$(x_{\rm t}, y_{\rm t})$	Target location of mobile node
$(x_{\rm tc}, y_{\rm tc})$	Center of target circle
$(x_{\rm cross}, y_{\rm cross})$	Intersection of the target circle and the connecting line of the mobile node and the center of the target circle
$(x_{\rm o}, y_{\rm o})$	Original location of node
$\beta_{\rm t}$	Target orientation
d	Distance of the node to the target location
E	Actuation energy consumption
θ	Angle of linking line
$E_{\rm r}$	Rotation energy consumption

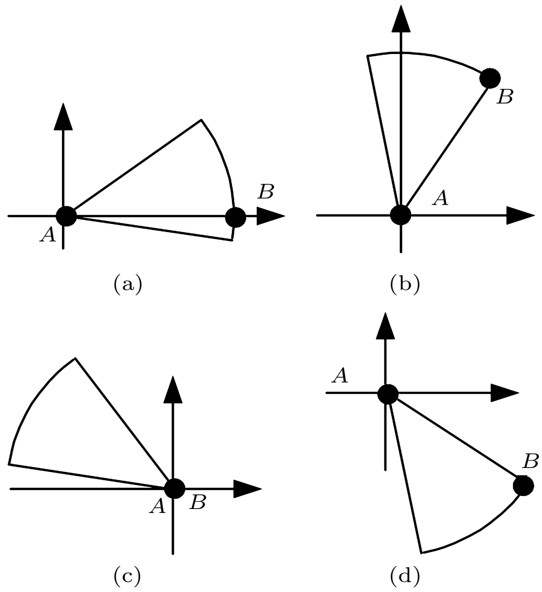
4.1 Determination of Target Location

The position of the target circle is labeled by its center $(x_{\rm tc}, y_{\rm tc})$, which is the point with the largest x-coordinate in the FoV of the ancestor node, and can be calculated as follows (see Fig.2).

$$x_{\rm tc} = \begin{cases} x_{\rm an} + r_s, & \text{if } 2\pi - \dfrac{\alpha}{2} \geqslant \beta_{\rm an} \leqslant 2\pi, \\ x_{\rm an} + r_s, & \text{if } 0 \leqslant \beta_{\rm an} \leqslant \dfrac{\alpha}{2}, \\ x_{\rm an} + r\cos(\beta_{\rm an} - \dfrac{\alpha}{2}), & \\ \quad \text{if } \dfrac{\alpha}{2} \leqslant \beta_{\rm an} \leqslant \dfrac{\pi + \alpha}{2}, & \\ x_{\rm an}, & \text{if } \dfrac{\pi}{2} + \dfrac{\alpha}{2} \leqslant \beta_{\rm an} \leqslant \dfrac{3\pi}{2} - \dfrac{\alpha}{2}, \\ x_{\rm an} + r_s\cos(\beta_{\rm an} + \dfrac{\alpha}{2}), & \\ \quad \text{if } \dfrac{3\pi - \alpha}{2} \leqslant \beta_{\rm an} \leqslant 2\pi, & \end{cases}$$

$$y_{\rm tc} = \begin{cases} y_{\rm an}, & \text{if } 2\pi - \dfrac{\alpha}{2} \geqslant \beta_{\rm an} \leqslant 2\pi, \\ y_{\rm an}, & \text{if } 0 \leqslant \beta_{\rm an} \leqslant \dfrac{\alpha}{2}, \\ y_{\rm an} + r_s\sin(\beta_{\rm an} - \dfrac{\alpha}{2}), & \\ \quad \text{if } \dfrac{\alpha}{2} \leqslant \beta_{\rm an} \leqslant \dfrac{\pi + \alpha}{2}, & \\ y_{\rm an}, & \text{if } \dfrac{\pi}{2} + \dfrac{\alpha}{2} \leqslant \beta_{\rm an} \leqslant \dfrac{3\pi}{2} - \dfrac{\alpha}{2}, \\ y_{\rm an} + r_s\sin(\beta_{\rm an} + \dfrac{\alpha}{2}), & \\ \quad \text{if } \dfrac{3\pi}{2} - \dfrac{\alpha}{2} \leqslant \beta_{\rm an} \leqslant 2\pi, & \end{cases}$$

where $(x_{\rm an}, y_{\rm an})$ is the coordinate of the ancestor, and $\beta_{\rm an}$ is its sensing direction.



(a) (b) (c) (d)

Fig.2. Center of target circle B $(x_{\rm tc}, y_{\rm tc})$ of an ancestor node A. (a) $2\pi - \frac{\alpha}{2} \geqslant \beta_{\rm an} \leqslant 2\pi$ or $0 \leqslant \beta_{\rm an} \leqslant \frac{\alpha}{2}$. (b) $\frac{\alpha}{2} \leqslant \beta_{\rm an} \leqslant \frac{\pi+\alpha}{2}$. (c) $\frac{\pi}{2} + \frac{\alpha}{2} \leqslant \beta_{\rm an} \leqslant \frac{3\pi}{2} - \frac{\alpha}{2}$. (d) $\frac{3\pi-\alpha}{2} \leqslant \beta_{\rm an} \leqslant 2\pi$.

Depending on the relative positions of mobile sensors with respect to the target circle and the FoV of an ancestor node, sensors within the communicating region of an ancestor node can be classified into four categories.

1) *Node Type* 1. Nodes located inside the FoV of the ancestor are categorized as type 1. Nodes C and D in Fig.3(a) are of this type, as they lie within the sensing range of ancestor node A and the target circle centered at point B.

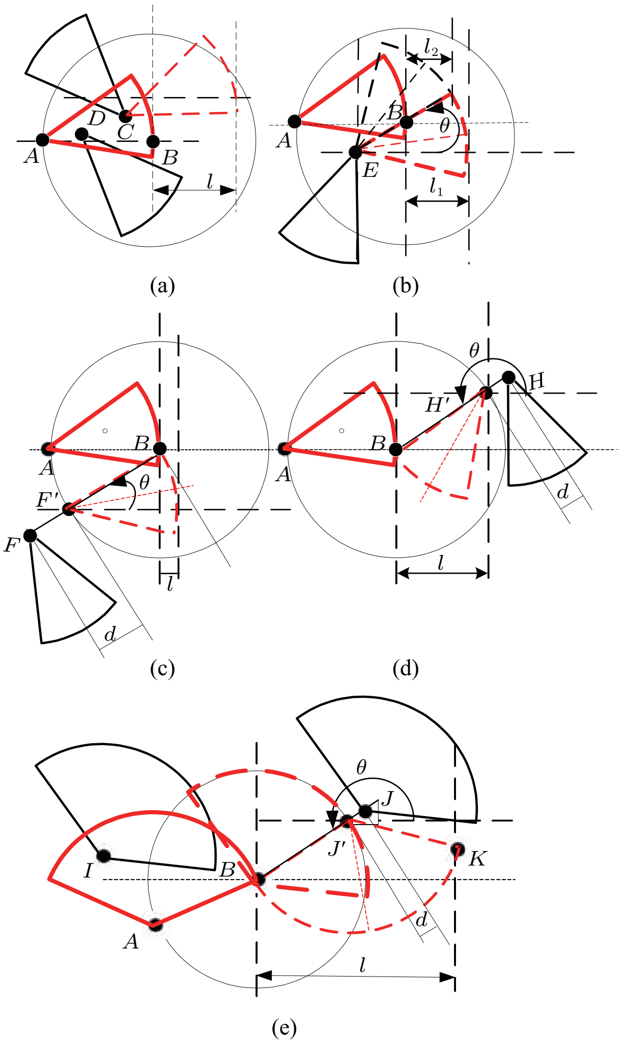


Fig.3. Target circle centered at B of ancestor node A and the categories of its surrounding neighbor node. (a) Type 1 nodes (C, D) can form the barrier by clock-wise or anti-clockwise rotation. (b) Type 2 node (E) and its target orientations (dashed sectors). (c) Type 3 node F and its target position F'. (d) Type 3 node H and its target position H'. (e) Type 4 node I and its target position B. The angle θ between the lines connecting the target position of nodes of type 1, type 2 or type 3, to the center of target circle B and the x-axis is defined.

2) *Node Type* 2. Nodes of this type lie outside of the FoV of the ancestor either within or on the target circle. Node E in Fig.3(b) is out of ancestor A's FoV while within target circle B. It is then categorized as type 2.

According to Theorem 1, nodes of these two types can form barrier coverage merely through rotating around their original locations. As shown in Fig.3(a) and Fig.3(b), rotating a certain angle around the initial location of nodes C and E to a position indicated by the red dotted sector, these nodes form barrier coverage with ancestor node A.

Clearly, depending on its position and orientation, a node contributes differently on the extension of a barrier (called barrier gain l) . The barrier length formed with ancestor node A and candidate node C in Fig.3(a) is larger than the one formed with candidate D. In other words, node C has larger gain than node D. In order to reduce the number of nodes required to form a directional barrier of the given length, nodes of these two types are considered, and the one with maximum barrier gain (denoted by $l_{\max}$) might be selected as the candidate relay sensor. However, node C might not be optimal, as it consumes more energy on adjusting its sensing direction compared with that required by node D, leading to small lifetime of the constructed barrier. As a consequence, the combined effect of barrier gain and energy consumption should be considered.

3) *Node Type* 3. Nodes of this type are characterized by their positions being outside of both the FoV and the target circle of an ancestor node. Obviously node F in Fig.3(c) and H in Fig.3(d) are of this type.

As opposed to the previous types, constructing the barrier with the node of this type requires both rotation and mobility capability. Theorem 2 sketches out the strategy for finding the optimal target location.

Theorem 2. *In order to form barrier coverage with the least displacement for type* 3 *nodes, the target position is determined by the intersection point between the target circle and a line, and this line connects the candidate node's original position to the center of the target circle.*

Proof. According to Theorem 1, the optimal target position must be either inside or on the target circle. Suppose an inside point L' (see Fig.4) is the optimal target position of candidate node F (type 3). The least displacement from the original position F to L' is line $\overline{FL'}$. This line must intersect with the target circle at point L, at which node F can form a directional barrier with less displacement. Thus the optimal target position must be on the circle.

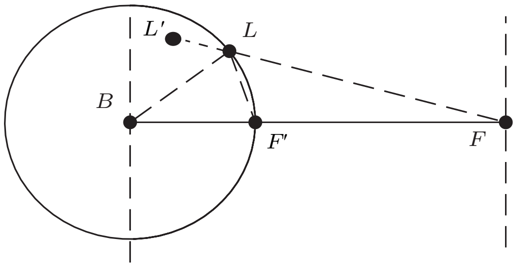


Fig.4. Ways of determining the optimal target location to sensors out of the target circle.

To proceed, suppose that the line connecting the center of the target circle B and the node's original position F intersects the circle at F', as shown in Fig.4. A triangle composed of points B, E and any point on the circle L has the relation: $\overline{BF}=\overline{FF'}+\overline{F'B}<\overline{BL}+\overline{LF}$. As L and F' are points on the circle, i.e., $\overline{BL}=\overline{BF'}$, the relation $\overline{F'F}<\overline{LF}$ holds true for any points on the circle expect F, i.e., F' is the point that requires the least displacement to form a barrier with ancestor node A. □

Apparently, applying Theorem 2, the target positions of candidate nodes F and H in Fig.3(c) and Fig.3(d) respectively can be determined. After moving to the target locations (F' and H'), these nodes are treated as type 2. Rotating around the target positions with an angle, these nodes could form barrier coverage with ancestor A. The rotating angle is determined by the original sensing direction and the line connecting the target location and point B (see the following Subsection 4.2 for detailed discussion).

4) *Node Type* 4. Nodes of this type lie within the ancestor node's FoV but out of the target circle.

Theorem 3. *Nodes of type* 4 *only exist in cases where the ancestor nodes have a sensing angle* $\alpha>\frac{\pi}{3}$.

Proof. The largest chord within the FoV of the sensor with sensing angle α and radius r_s is determined as $Sup[r_s,2r_s\sin(\alpha/2)]$, which exceeds r_s only when $\alpha>\pi/3$. The target circle is drawn with radius r_s at the point with extreme x-coordinate in the FoV of the ancestor node. Suppose that the sensing angle of an ancestor node is $\alpha\leqslant\frac{\pi}{3}$, the distance between the center of the target circle and any point within the FoV is less than $Sup[r_s,2r_s\sin(\alpha/2))]\leqslant r_s$. Thus it must lie within the target circle. This contradicts the definition of node type 4. □

A clear example of this type is node I in Fig.3(e), as it lies within the FoV of ancestor node A, while out of the target circle centered at point B.

In order to take the full advantage of rotation capability (consuming less energy) and reduce the number of nodes required to form a barrier, all types of nodes should be considered as the candidate relay sensors depending on their weight w. Under this criterion, there is no sense to move a type 4 node to a target location determined according to Theorem 2, as it contributes to zero gain. However, when it is moved to the center of the target circle, a gain as large as r_s can be obtained.

Summarizing the previous discussions, the target positions of the relay sensors are determined according to (2):

$$(x_{\rm t},y_{\rm t})=\begin{cases}(x_{\rm o},y_{\rm o}), & \text{Type 1 or 2},\\ (x_{\rm c},y_{\rm c}), & \text{Type 3},\\ (x_{\rm tc},y_{\rm tc}), & \text{Type 4},\end{cases}\qquad(2)$$

where $(x_{\rm o},y_{\rm o})$ $(x_{\rm tc},y_{\rm tc})$, and $(x_{\rm c},y_{\rm c})$ are its original location, the center of target circle, and the intersection of the target circle and the connecting line respectively.

4.2 Selection of Target Orientation

The optimal target locations determined in Subsection 4.1 allow to establish direction barriers with minimal displacement energy expenditure, without guaranteeing its optimal gain l. The barrier should be further optimized to provide the maximum gain with the minimum rotating energy consumption. After the optimal position of the relay sensor has been determined, there is no difference between node types 1 and 4. The same goes to types 2 and 3. From Fig.3(a) and Fig.3(e), it can be seen that there is no need to rotate the type 1 (4) relay sensor in order to maximize its gain as long as its original sensing direction β is in the range $0\leqslant\beta\leqslant\alpha/2$ or $2\pi-\alpha/2\leqslant\beta\leqslant 2\pi$. While β is in range of $\alpha/2\leqslant\beta\leqslant\pi$, it should be adjusted to $\alpha/2$. If it is out of these ranges, its sensing direction needs to be adjusted to $2\pi-\alpha/2$. (3) details the strategy.

$$\beta_t^{1,4}=\begin{cases}\beta, & \text{if } 0\leqslant\beta\leqslant\alpha/2,\\ \beta, & \text{if } 2\pi-\alpha/2\leqslant\beta\leqslant 2\pi,\\ \alpha/2, & \text{if } \alpha/2\leqslant\beta\leqslant\pi,\\ 2\pi-\alpha/2, & \text{if } \pi<\beta\leqslant 2\pi-\alpha/2.\end{cases}\qquad(3)$$

Determining the optimal sensing direction ($\beta_t^{2,3}$) of type 2 and type 3 nodes requires more effects. As shown in Fig.3(b), node E brings different barrier gain l and weight w depending on its sensing direction (of which its two sidelines of the sensing sector overlap the center of target circle B). To describe this effect, we introduce θ, the angle between the vector $\boldsymbol{EB}$ (from the target position of the candidate relay sensor E to the center of target circle B) and the x-axis. We then denote the barrier gain and weight as l_1 and w_1 respectively when the node direction is adjusted to $\theta - \alpha/2$ (B on the up boundary of the sensing region), and l_2 and w_2 respectively when β is adjusted to $\theta + \alpha/2$ (B on the low boundary). To meet the demand of barrier construction with less sensor nodes and longer lifetime, both the sensing directions should be considered. The decision on which direction should be chosen depends on the potential weights the different orienting angles can bring. (4) summarizes the criterion of choosing the optimal sensing directions of relay node of type 2 or 3.

$$\beta_t^{2,3} = \begin{cases} \theta - \alpha/2, \text{ if } w_1 \leqslant w_2, \\ \theta + \alpha/2, \text{ if } w_1 > w_2. \end{cases} \quad (4)$$

4.3 Computation of Barrier Weight

According to (1), barrier weight describes the quality of each potential sensor node when it is recruited as a barrier node. It is a key factor that determines the barrier quality. To calculate barrier weight, the potential gain and the related energy consumption have to be determined.

When a node is displaced and rotated to form a directional barrier coverage with ancestor nodes by applying the previously stated strategies, the center of target circle $(x_{\text{tc}}, y_{\text{tc}})$ is the point with the largest x coordinate within the FoV of the ancestor before adding a relay node. After the relay sensor is added, the point with extreme x coordinate in the barrier's coverage region is extended to $(x_{\max}, y')$. The barrier gain that a candidate relay sensor brings can be calculated as:

$$l = x_{\max} - x_{\text{tc}}. \quad (5)$$

Theorem 4. *Nodes with sensing angle $\alpha \leqslant \pi/3$ bring maximal and minimal barrier gain r_s and 0, respectively. Nodes with $\alpha > \pi/3$, type 1, 2 or 3 bring barrier gain at most $2r_s\sin(\frac{\alpha}{2})$ and at least 0, while for type 4 a fixed barrier gain r_s can always be obtained by rotation.*

Proof. Constructing a direction barrier requires one of the two sidelines of the FoV of descendant nodes intersect with the center of the target circle. The largest chord in the FoV of sensor with $\alpha \leqslant \pi/3$ is r_s. When the whole largest chord is used to extend the barrier, a maximal gain r_s obtains. As a node cannot affect ancestors' existing coverage range, its minimal gain is 0. Same reasoning can be applied to nodes of type 1, 2 or 3 with $\alpha > \pi/3$, where the maximal chord in the FoV is $2r_s\sin(\alpha/2)$. As node type 4 locates at the center of the target circle, rotating its sensing direction to have x-axis pass through the arc of the FoV gives barrier gain r_s. □

Energy consumption, directly related to barrier lifetime, should be considered during barrier construction. In this subsection we formulate the energy required to reach the target location and orientation specified in Subsection 4.1 and Subsection 4.2, respectively . As the energy required to actuate sensors is far more beyond that required by communication[44], it is reasonable to just focus on actuation energy while ignoring that required for communication during this analysis.

Adjusting sensors to form barrier coverage typically requires locomotion and rotation, both of which consume the energy. However, applying strategies stated in Subsection 4.1, type 1 and type 2 nodes only require the rotation to form directional barriers. Thus the required energy can be expressed as:

$$E_r = \text{minimum}\{|\beta_a - \beta|J_r, (2\pi - |\beta_a - \beta|)J_r\}. \quad (6)$$

Here, β and β_a are the initial and the target orientations of the node, respectively. J_r indicates the energy required when rotating the sensor by a unit angle. Minimum is used to account for the fact that least energy consumption is achieved by rotating nodes clock-wisely or anti-clock-wisely.

Nodes of types 3 and 4 must move to the target location before adjusting its orientation. Accordingly, its total energy consumption E_c consists of two parts: locomotion and rotation, i.e.,

$$E_c = dJ_m + E_r, \quad (7)$$

where d stands for the distance that the node has to travel to reach the target location and J_m is the required energy per unit distance.

Theorem 5. *The expected rotating energy consumption $\bar{E}_r^e$ of node types 2 and 3 is $\frac{\pi\times J_r}{2}$.*

Proof. Nodes are randomly deployed with their initial orientation angle β in the range $[0, 2\pi]$. Node types 2 and 3 have target orientation angle β_a independent of β. According to (6), the expected rotational energy is

$$\bar{E}_r^e = \frac{J_r}{2\pi}\int_0^{2\pi} \text{minimum}\{|\beta_t - \beta|, (2\pi - |\beta_t - \beta|)\}\mathrm{d}\beta.$$

To proceed, we split our discussion into two parts: 1) $0 \leqslant \beta_t < \pi$ and 2) $\pi \leqslant \beta_t < 2\pi$. Under the first condition, $\bar{E}_r^e = \frac{J_r}{2\pi}(\int_0^{\beta_t}(\beta_t - \beta)\mathrm{d}\beta + \int_{\beta_t}^{\beta_t+\pi}(\beta - \beta_t)\mathrm{d}\beta + \int_{\beta_t+\pi}^{2\pi}(2\pi - \beta + \beta_t)\mathrm{d}\beta) = \frac{\pi\times J_r}{2}$. When β is in range $[\pi, 2\pi)$, $\bar{E}_r^e = \frac{J_r}{2\pi}(\int_0^{\beta_t-\pi}(\beta_t - \beta)\mathrm{d}\beta + \int_{\beta_t-\pi}^{\beta_t}(\beta - \beta_t)\mathrm{d}\beta + \int_{\beta_t}^{2\pi}(2\pi - \beta + \beta_t)\mathrm{d}\beta) = \frac{\pi\times J_r}{2}$.

In summary, $\bar{E}_r^e = \frac{\pi\times J_r}{2}$ holds true for any β_t. □

With the energy expenditure E required on position adjustments and resulted gain l, the potential barrier weight w of each candidate relay sensor can be calculated according to (1). A barrier constructed with sensors of low barrier weight w is expected to provide long lifetime without sacrificing abundant sensors.

5 Energy-Efficient Distributed Directional Barrier Construction Based on Target Circle (D-TarC)

To meet the requirements of constructing a barrier with the least sensor nodes and the longest lifetime, each sensor should bring barrier gain as large as possible, with least energy consumed on adjusting its position and orientation in order to bring this gain. Typically, each sensor can give gain as large as r_s by spending unlimited energy on its position adjusting. As a consequence, it reduces barrier lifetime. Thus, a compromise should be made between them. The concept barrier weight w describes the energy required to bring unit amount of barrier gain. Clearly, the smaller the weight, the better a sensor node contributes to barrier construction.

Based on this, we here propose an effective barrier construction algorithm called energy-efficient distributed directional barrier construction based on target circle (D-TarC). Similar to the algorithm in [11,16], the basic idea is illustrated in Fig.5: a node on the left end boundary is selected as the initiator, which is seen as the ancestor node.

To select a relay sensor to a directional barrier, the ancestor broadcasts its target circle by $TargetCircleBroadcast()$ to its neighbors. Upon receiving this message, each neighboring sensor calls $WeightReport()$ to compute the desired location and orientation for it to form barrier coverage with the ancestor and report its potential weight w to the ancestor node. After receiving responses from all the neighbors, the ancestor node chooses the one with minimum w as successor and informs it. The successor confirms the message by adjusting to the desired location and orientation, and declares itself as the ancestor node to be relayed. This procedure is repeated until the sensing sector of the current barrier member covers the right end boundary.

A sensor communicates with its neighbors. To build a barrier with the aforementioned strategy, the information about nodes' location and weight should be transferred. In the following, we detail the algorithm and communication protocol.

5.1 D-TarC Construction Algorithm

This subsection details the algorithm for implementing the D-TarC method. D-TarC builds a k-barrier based on a distributed approach. To start, k sensors whose sensing regions intersect the most left boundary L_l of the ROI need to be selected as initiators. These sensors will be seen as the first ancestor of each barrier, and choose their successor to relay the barrier.

Function *Initializing*() gives the pseudo code for finding initiators (see Algorithm 1). This function is executed only once, i.e., right after the start-up of sensors. To start, sensor v_i checks the relationship between its sensing region and the most left boundary of the region to be monitored L_l. If they contain some region in common, v_i calculates its potential contribution (or gain l_i) to the barrier as $l_i = \max_x(v_i) - L_l^x$. Then it recommends itself as the candidate of initiator by broadcasting a recommendation message (REC, l_i, v_i) using *geosend*(). Here $\max_x(\cdot)$ stands for getting the maximum x coordinate of some region. At the same time, it collects recommendation messages (REC, l_j, v_j) delivered by sensor v_j. For each candidate v_j, its potential contribution l_j and ID v_j are sent to L and C, respectively (lines 5–8). After receiving all the recommendation messages, it selects k sensors with the maximum gain l in C (line 9). If sensor v_i is one of the initiators, it declares itself as the initiator and the

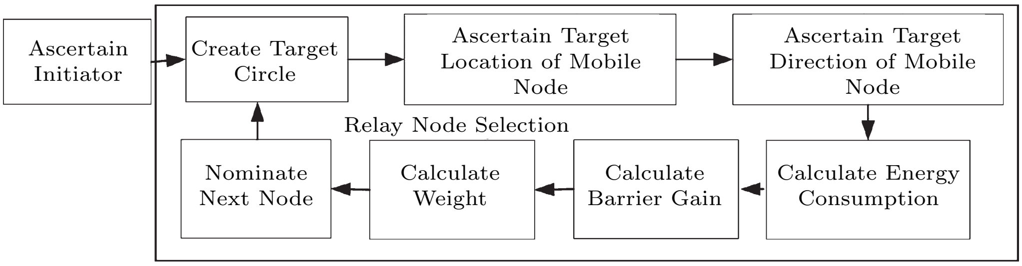


Fig.5. Chart of task flow for implementing D-TarC.

first ancestor $anc = v_i$, and moves out from the initial sensor set S to the barrier set B (lines 12–15).

Algorithm 1. D-TarC: *Initializing*() for Each Sensor v_i

```
1: if $reg(v_i) \cap L_w \neq \emptyset$ then
2:     $l_i = \max_x(v_i) - L_w^x$
3:     $geosend$(REC, $l_i$, $v_i$)
4:     Wait until (all REC messages from initial candidates have been received)
5:     for <REC, $s_j$, $l_j$> $\in RecMsgSet$ do
6:         $L \leftarrow L \bigcup l_j$
7:         $C \leftarrow C \bigcup v_j$
8:     end for
9:     Initiators $\leftarrow \max_k\ (L, C)$
10: end if
11: for $z = 1 : k$ do
12:     if $v_i = Initiators(z)$ then
13:         $anc(z) = v_i$
14:         $B(z) \leftarrow B(z) \bigcup v_i$
15:         $S \leftarrow S \setminus v_i$
16:     end if
17: end for
```

After initiators have been determined, each of them needs to inform their neighbors the way how to construct barrier coverage with them by sending the target circle information. Function $TargetCircleBroadcast()$ performs this task (see Algorithm 2). If a sensor node v_i in barrier set B is the ancestor, it creates a target circle at the point with maximum x coordinate in its sensing region, and delivers it out to its neighbors. At the same time, it collects weight messages delivered by potential successor candidates. For each weight message from candidate node v_j, its weight information w_j and its ID v_j are sent to W and C, respectively (lines 7–10). After having received the weight messages from all candidates, its successor is chosen from C that gives the minimal weight in W. After the successor is chosen, v_i sends the selection result. If the selection is confirmed, the successor performs the adjustments according to the target circle. It is then added to the barrier set $B(z)$ and appointed as the ancestor of the barrier (lines 14–17). If no response has been received for a period of time, the ancestor selects again the successor (lines 18–22).

For each un-used node v_i in set S, it should report its weight after receiving $TargetCircle$ messages from ancestors. Function *WeightReport*() performs this task (see Algorithm 3). Before sending a weight message to the ancestor who initiates the $TargetCircle$ message, its barrier weight w_i must be calculated first.

k barriers are formed simultaneously, the un-used node v_i could receive many *TargetCircle* messages. After receiving *TargetCircle* messages, the target circle with minimal distance fully determines the type it belongs to (line 2). To recommend itself as a candidate relay sensor, it must report its weight if it forms a barrier with the ancestor. If sensor v_i in set S lies within the FoV of the ancestor (anc), this sensor calculates its distance to the center of the target circle T_c as $dist(v_i, T_c)$. If this distance is greater than r_s (i.e., type 4), v_i calculates the required

Algorithm 2. D-TarC: *TargetCircleBroadcast*() for Each Sensor $v_i \in B(z)$

```
1: if $v_i = anc(z)$ then
2:     C = $\emptyset$
3:     Calculate its $(x_{\max}, y_{\max})$
4:     Create target circle
5:     $geosend(TargetCircle,\ anc(z))$
6:     Wait until (all weight messages from successor candidates have been received)
7:     for $(Weight,\ v_j\ ) \in WeightMsgSet$ do
8:         $W \leftarrow W \bigcup w_j$
9:         $C \leftarrow C \bigcup v_j$
10:    end for
11:    $Successor(z) \leftarrow \min(W, C)$ // get the node with minimal weight as successor
12:    $geosend(Successor,\ Successor(z))$
13:    Wait for a moment
14:    if response is received then
15:        $B(z) \leftarrow B(z) \bigcup Successor(z)$
16:        $anc(z) = Successor(z)$
17:        $S \leftarrow S \setminus Successor(z)$
18:    else
19:        $W \leftarrow W \setminus w_j$
20:        $C \leftarrow C \setminus v_j$
21:        Go back to line 11
22:    end if
23: end if
```

Algorithm 3. D-TarC: $WeightReport()$ for Each Sensor $v_i \in$ S

```
1: while TargetCircles are received do
2:     Determine its type by target circle with minimal distance
3:     if $v_i \in$ type 1 or $v_i \in$ type 4 then
4:         if $dist(v_i, T_c) \geqslant r_s$ then
5:             $d = dist(v_i, T_c)$
6:         else
7:             $d = 0$
8:         end if
9:         Determine $\beta_t$ by (3)
10:    else if $v_i \in$ type 2 or $v_i \in$ type 3 then
11:        if $dist(v_i, T_c) \geqslant r_s$ then
12:            $d = dist(v_i, T_c) - r_s$
13:        else
14:            $d = 0$
15:        end if
16:        Determine $\beta_t$ by (4)
17:    end if
18:    $E_{ci} = dJ_m + |\beta_t - \beta_i| J_r$
19:    Calculate $l_i$ by (5)
20:    $w_i = E_{ci}/l_i$
21:    $RespondToAnc(Weight,\ w_i,\ v_i)$
22: end while
23: while Successors are received do
24:     Determine one with minimal distance as its ancestor
25:     $RespondToAnc(Successor)$
26: end while
```

displacement to form a barrier with the ancestor $d = dist(v_i, T_c)$ according to (2); otherwise $d = 0$. After the required displacement being made, there is no difference between types 1 and 4. Therefore, the requirement sensing direction β_t can be determined using (3) (see lines 11–17).

For sensor node v_i out of the ancestor's FoV, if its distance to the center of the target circle $dist(v_i, T_c)$ is larger than r_s (type 3), it calculates the required displacement $d = dist(v_i, T_c) - r_s$; otherwise $d = 0$. Its target orientation is calculated by (4). After its potential gain l_i and actuation energy E_{ci} are determined, its weight for constructing a barrier with the ancestor is determined and reported to the ancestor node (lines 18–20).

If there are many nodes sending successor messages, v_i selects the one with minimal distance as its ancestor, and responds to this successor message (lines 23–26).

The characteristics of this algorithm are as follows.

- Our method is in distributed manner. After receiving many candidate nodes' weights, each barrier member selects the node with the minimum weight as its relay sensor to extend the barrier.
- It speculates all target locations of mobile node with 0-1 sensing model, and selects the optimal target location as the actual target location of mobile nodes. The method in [40] only considers four target locations of mobile nodes with probabilistic sensing model with a changing angle.

5.2 D-TarC Implementation

As proposed in Subsection 5.1, during barrier construction nodes with their FoVs intersecting with the left end boundary of RoI need to broadcast their recommendation messages as initiators and start collecting these messages at the same time. Ancestor nodes need to send their target circle messages to their neighbors and start collecting neighbors' weight message at the same time. Candidate nodes must report their weights to each of ancestors upon receiving each target circle message.

Sensor nodes perform their tasks depending on their roles. Initially all sensors have the same role, i.e., candidate relay sensor. Immediately after being booted, all these nodes start the initialization procedure by checking its position related to the left end boundary. If they have common intersection, these nodes broadcast their recommendation messages to their neighbors and collect recommendation messages from their neighbors concurrently. Recommendation message REC contains node ID v_i and its gain l_i. $RevMsgSet$ is used to record the recommendation messages from potential initiator candidates. Node v_i broadcasts itself as the initiator when its gain l_i is among the largest k-th candidates, and changes its function role identifier as used, which is the first ancestor of the barrier.

After being declared as an ancestor, it immediately broadcasts a $TargetCircle$ message to its neighbors. At the same time it starts to collect response messages $Weight$ from its neighbor. The ancestor chooses the one with minimum w among the replied sensors and informs it by sending a $Successor$ message. If this choice is confirmed, it would adjust its position and orientation. After finishing the required adjust, it declares itself as the ancestor and changes its role as used. This procedure continues until the most right boundary of the RoI is covered by the barrier.

The ancestor is required to wait all weight messages and response of the $Successor$ message, and neighbor nodes are also required to wait the $TargetCircle$ message. Packet loss, collisions and communication delays impact the waiting time. Since the communicating range is r_c, the maximum waiting time is $2r_c/c$, where c is the electromagnetic wave propagation rate (speed of light).

It assumes the total number of nodes is N, the first barrier member is selected from the N nodes, and the second is selected from the $(N-1)$ nodes, which is repeated until the barrier is formed. In the worst case, it exhausts all N nodes. Therefore, the overall time complexity is $O(N^2)$.

Barrier members need to broadcast the target circle message, mobile nodes need to broadcast their own energy consumption, and the communication complexity is $O(N)$.

6 Performance Evaluation

6.1 Effects of Target Circle

Target location of relay sensor determines whether it could form a strong barrier with its ancestor. Different guidelines are used to determine the target location of the relay sensor. [20] uses the right most point B (see Fig.6) within the ancestor's FoV as the only position to put the relay sensor (single mode). Under this scheme, each relay sensor contributes a barrier gain as large as its sensing radius r_s. The authors[21] further noticed that point T_2 with the distance r_s away to T_1 along the belt direction can also be selected as target location (double mode), as it provides the same gain but might consume less energy. The proposed method (D-TarC) looses the demand for providing the largest gain by allowing all possible locations on a circle centered at T_1. This strategies focus on the efficiency of adjusting sensors.

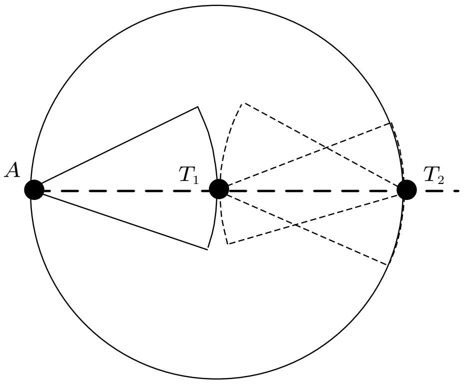
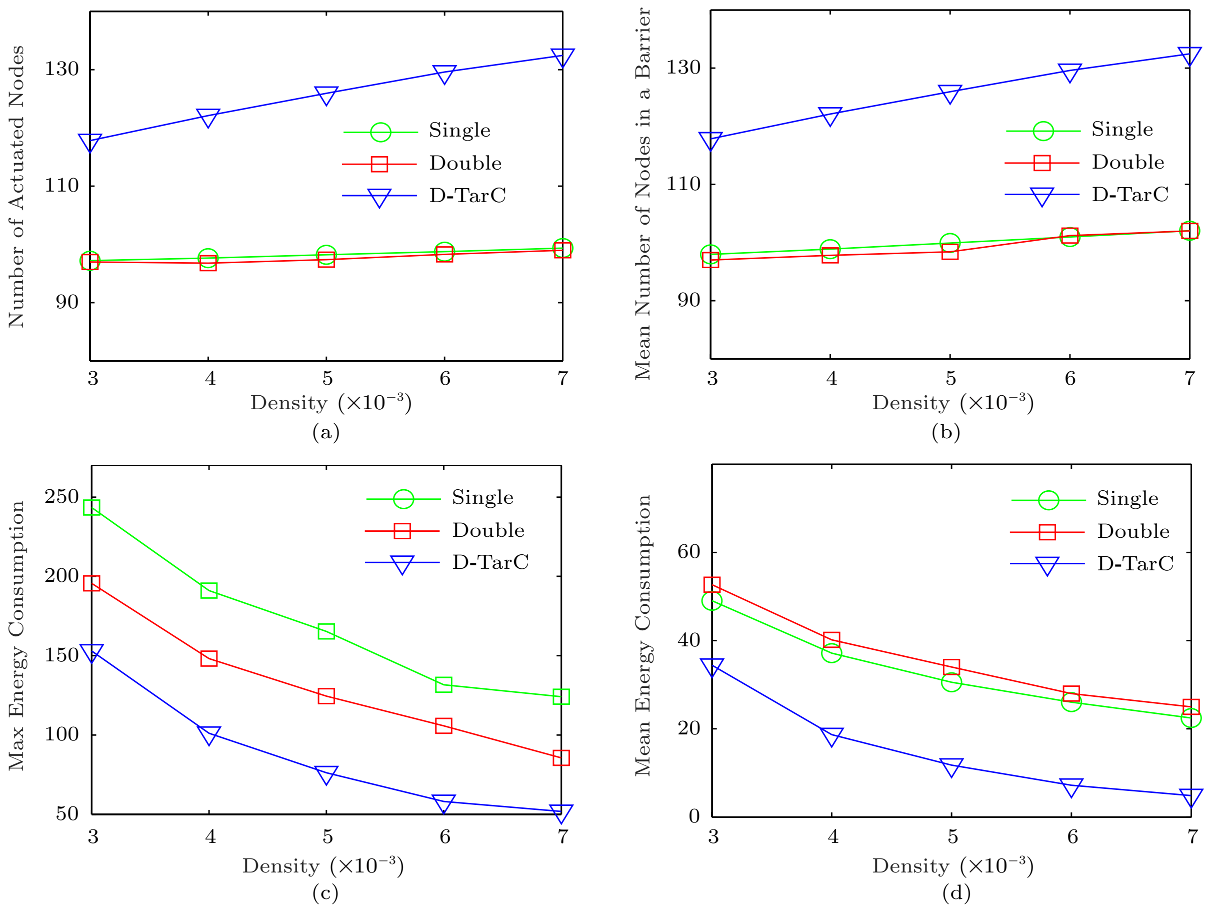


Fig.6. Different strategies used to find the target location for the relay sensor. The right most point (T_1) within FoV of the ancestor sensor A is used as the only target position in [20]. Either T_1 or T_2 (r_s away to point T_1) can be chosen depending on the energy required to adjust its position and orientation [21].

Fig.7 shows a comparison of parameters related to the barriers constructed using different target locations. During the barrier construction process, each involved node consumes a certain amount of energy due to its moving and rotation, as specified in (7). The maximum energy consumption is defined as the largest one among these nodes' energy consumption, and the mean energy consumption is defined as the average value of these nodes' energy consumption. Single-target and double-target schemes show no difference in terms of the number of nodes needed to be adjusted and the mean number of nodes in a barrier, as both of them require each relay sensor contribute r_s to the gain (Fig.7(a) and Fig.7(b)). However double-target scheme significantly reduces the maximum energy required for adjusting sensors' position in a barrier (see Fig.7(c)). Under the D-TarC scheme, relay sensors can be in any point within the target circle, as long as their input-output ratio (w) is low. This leads to a significant reduction in energy consumption, i.e., increase in barrier lifetime.



(a) (b) (c) (d)

Fig.7. Comparison of strong barrier construction strategies using different target locations, where single-target position is used in [20], and double-target location in [21]. (a) Number of actuated nodes during construction. (b) Average number of nodes in a barrier. (c) Maximum energy consumed during construction. (d) Mean energy consumed by nodes in a barrier.

Although more sensors are needed in a barrier, its lifetime expands significantly benefitting from less energy consumption.

6.2 Effectiveness of Proposed Method

Recalling the object of constructing directional barrier of the longest lifetime with the least sensor nodes, the method proposed here shows advantages compared with other methods reported in [13, 19]. First of all, in a distributed scheme, each sensor only needs information from its neighbors. But with the centralized scheme, sensors must report their status information to the central sink, and the sensor at the edge of the barrier needs more energy to report its information to the sink, compared with the node near the sink. As a consequence, the lifetime of barrier becomes short.

Second, our scheme balances energy consumption and resulted gain during its construction. Due to random initial distribution of sensors, rearrangement is required in order to provide desired service. This consumes energy. Selecting relay sensor with minimum energy expenditure on position adjusting leads to the augmentation of required sensor nodes[13]. Sensors close to the ancestor typically require less energy on position adjustment to form the barrier with the ancestor, and at the same time, contribute less to barrier gain. As a consequence, more sensors might be needed.

One might argue that this strategy prolongs service lifetime. In contrast, it can be the opposite. Most effective way to prolong barrier service time is achieved by constructing k-barrier and cycling them[30, 41], i.e., the larger k, the longer the barrier lifetime. In a field with given sensor nodes distributed, constructing one barrier with more sensor nodes reduces the probability of building additional barriers. When maximum barrier gain is used as the selecting strategy, sensors with extreme large energy consumption would be selected. Constraint with limited battery capacity directly reduces barrier lifetime. Under the proposed scheme, an ancestor selects its descendant according to the combined effect of barrier gain and energy consumption. That is to say, a barrier is constructed using less nodes but without sacrificing its lifetime. This is clearly demonstrated in Fig.8. A 4-barrier coverage service is provided after applying the proposed strategy to a random deployment of 50 sensors in a 200 m × 200 m region.

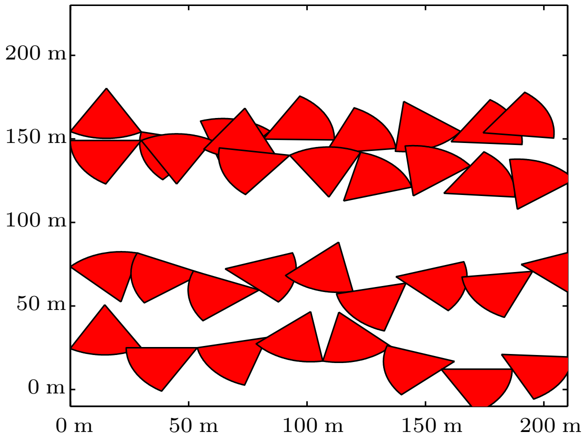


Fig.8. Example barrier formation under the proposed algorithm. Nodes might not contribute their full sensing range to the barrier due to efficient energy management.

6.3 Simulation Environment and Parameter Definition

To quantify the advantages of the proposed method, we carry out a set of simulations to evaluate the performance of the D-TarC scheme using Matlab. Table 2 details the parameters used in the simulations that produce the results presented below.

Table 2. Parameters Used in Simulations

Parameter	Value
area	200×300 m^2
J_m	3.6 J $\times$ m^{-1}
r_s	20 m
E	10^5 J
θ	$\pi/4$
J_r	1.8 J
R_c	$2r_s$

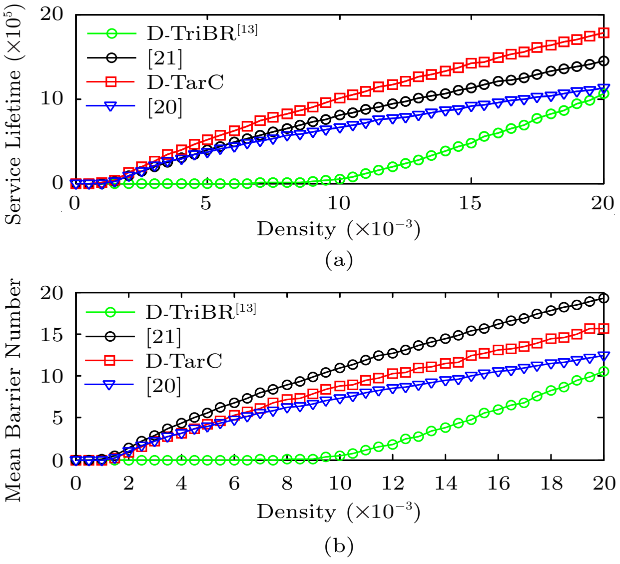
Recall the purpose of strong barrier coverage[5], its quality can be represented by: 1) the lifetime that a barrier can provide the coverage service; 2) the number of sensor nodes required for constructing a strong barrier coverage. Due to limited battery capacity, the service lifetime that a barrier can provide is fully determined by the minimal residual energy after adjusting its position and direction to form barriers. A barrier fails when there is one sensor running out of battery. Thus, a barrier's lifetime can be further represented as $L_b = (E_0 - E_{\max})/P_c$, where E_0 is the total energy of a sensor, $E_{\max}$ is the maximum energy that a sensor spends to form the barrier (please check Subsection 6.1), and P_c is the working power of barrier sensors after forming the barriers. In this paper, we set $P_c = 1$ J/s, that is, the consumed power is 1 J per second.

Diving deeper on the barrier surveillance, services can still be provided even though one barrier fails, as long as the other barriers can be established, especially when the timeshare scheme can be applied [34]. We define the service lifetime as the sum of lifetime of all constructed barriers. The service lifetime L_s is calculated in (8), where $E^j_{\max}$ is the largest energy consumption (spent on sensing-direction rotating and node moving) among the j-th barrier's members.

$$L_s = \sum_{j=1}^{k} L_b(j) = \sum_{j=1}^{k} \frac{E_0 - E^j_{\max}}{P_c}. \tag{8}$$

Here, the summation is done through all possible barriers established for each deployment.

Fig.9 shows the relation between service lifetime L_s after averaging over 1 000 realizations and sensor density. For comparison, same quantities are calculated using the D-TriBR method proposed in [13], methods in [20] and in [21], respectively. One can see that the D-TarC method shows the longest life expectance. All four methods show a linear relation between L_s and sensor density after density reaches some threshold (see Fig.9(a)). Same phenomena appears in the relation between the average number of barriers found in each deployment k and the sensor density (see Fig.9(b)). Since each barrier member has the largest gain r_s, the number of barriers found in [21] is larger than that of our method. However, its lifetime is less than that of our method because much energy consumption required to form barriers.

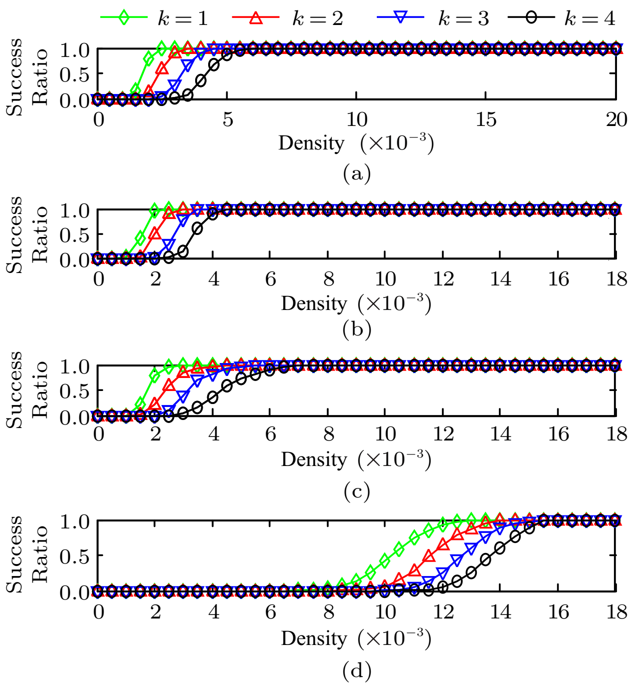


(a)

(b)

Fig.9. Comparison of the effective lifetime of the surveillance services provided by the barriers constructed using different strategies. D-TarC shows the longest life expectance against other methods.

The linear relation between sensor density and k suggests us to consider the probability for constructing k barriers under one deployment. Fig.10 shows the results. Compared with D-TriBR, the other three methods require much less sensors in order to provide same quality of service to RoI. Under the same sensor density, the other three methods establish more barriers. Although the lifetime of each barrier might be smaller than that built under D-TriBR strategy, the service time from D-TarC is much larger than that of D-TriBR. Compared with the method in [21], the D-TarC method requires a little more nodes to provide the same quality of coverage, because the barrier gain of barrier members in the method of [21] is larger than that of D-TarC.



(a)

(b)

(c)

(d)

Fig. 10. Constructing k-barrier using different strategies. (a) D-Tarc. (b) [21]. (c) [20]. (d) D-TriBR.

One might argue that the proposed method D-TarC might not be profitable, as it requires all the sensors to be of locomotive ability. The fact is that without locomotive ability, more sensors are required to provide the same quality of surveillance service, as a large set of them cannot form a barrier merely by rotating its sensing direction. To demonstrate this, we introduce deploy efficiency $\gamma = N_s/N$ defined as the ratio between the number of sensors N_s that contribute to provide services and the total number of sensors deployed N.

Fig.11 shows a comparison of the deploy efficiency between these four methods. At low sensor density conditions, the performance of three methods, which form barriers by exploiting both mobility and rotation capability, is far greater than that of D-TriBR forming barriers only by rotation capability, implying more sensors are required to compensate its inability of establishing barriers in a high sufficient way.

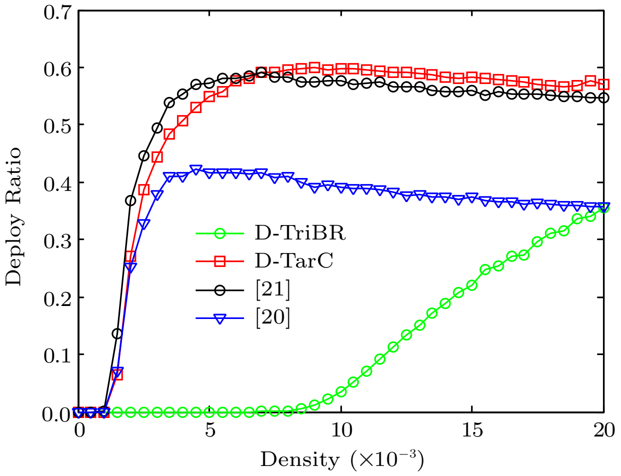


Fig.11. Comparison of deployment efficiency γ under different strategies. When sensors are deployed with a low density, none of them can be used. About 60% of sensors can contribute to barrier construction under D-TarC and [21] by increasing sensor density, while only 40% can be used under D-TriBR strategy and [20].

In sum, since D-TarC selects the node with the minimum weight to form barriers in distributed manner, it provides great service lifetime with a high deploy efficiency, although its barrier success ratio is slightly lower than that of method in [21]. The performance of D-TarC outperforms that of D-TRiBR and the method in [20].

6.4 Performance in Hybrid Networks

Concerning the relatively higher cost of mobile sensors and its unique merit, barrier construction schemes in hybrid network have been attracting research efforts[19]. The proposed method can be adapted to hybrid case, i.e., simply putting its weight w to the infinity for stationary sensors.

To test the effectiveness and the robustness of the method, we carry out a set of numerical simulations using same parameters as in [19]. Fig.12 shows the maximal number of barriers can be created in a belt area of size 100 m × 500 m. Simulations were done with parameters as same as in [19], i.e., the number of mobile sensors $\tau = 50$, $r_s = 20$ m and $\alpha = \pi/2$; the number of stationary sensors $n_s = 100$, $r_s = 20$ m and $\alpha = \pi/2$. Compared with the strong optimal scheme proposed in [19], our method gives comparable performance, expect in the case without mobile sensors deployed (see Fig.12(b)). In this case, due to small sensor density, the chances that there is at least one sensor within the target circle are low[45]. As a consequence, no barrier can be created. As long as a small fraction of mobile sensors is added, the chances of creating barriers improve greatly.

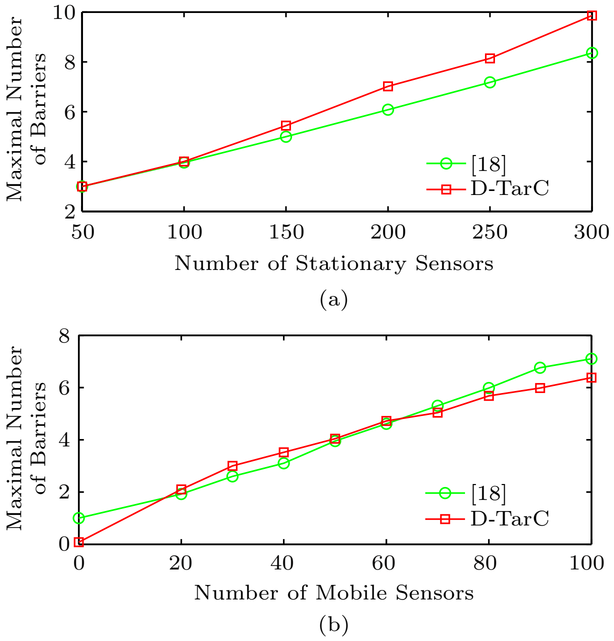
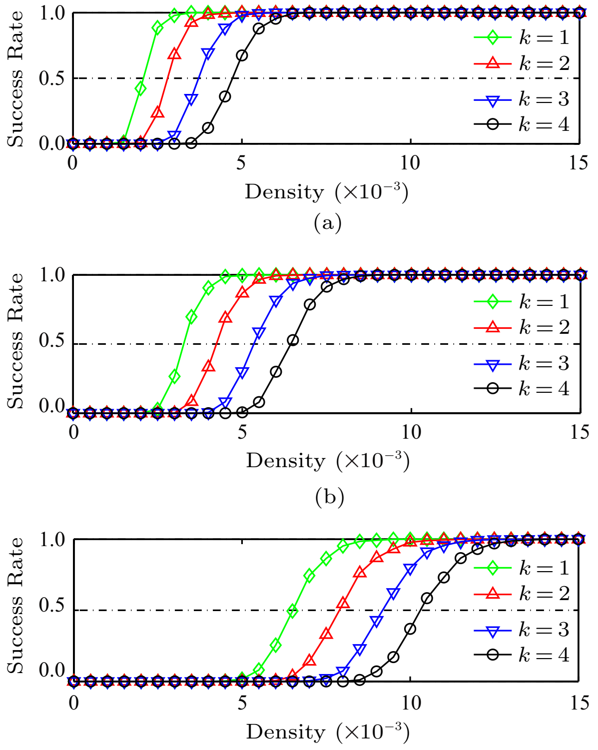


Fig.12. Maximal number of barriers constructed using different strategies within networks of different mobile sensors. Numerical results are generated using same parameters in [19], i.e., (a) number of mobile sensors $\tau = 50$, $r_s = 20$ m and $\alpha = \pi/2$, and (b) number of stationary sensors $n_s = 100$, $r_s = 20$ m and $\alpha = \pi/2$.

Based on the results presented above, it is reasonable to ask the question: how does the performance of the proposed method depend on locomotive ability of sensors? To this end, we introduce the parameter the fraction of sensors with locomotive ability in the network.

Fig.13 shows the probability of creating a set of barriers with the random deployment of sensors containing different locomotive fractions. Adding more sensors with locomotive ability eases the creation of k barriers (from top to bottom, the fractions are 0.8, 0.4 and 0.1, respectively).

We further extract the required sensor density at which the probability of creating k-barrier exceeds 50%, with the indentation that k barriers could be formed, as long as the density reaches the threshold value. Fig.14(a) shows the dependence of threshold density and the underlying locomotive sensor fraction. It is clear that adding a set of moving sensors in DNS significantly reduces the required number of sensors to be deployed [46], as it takes higher fraction of deployed sensors into use (see Fig.14(b)).

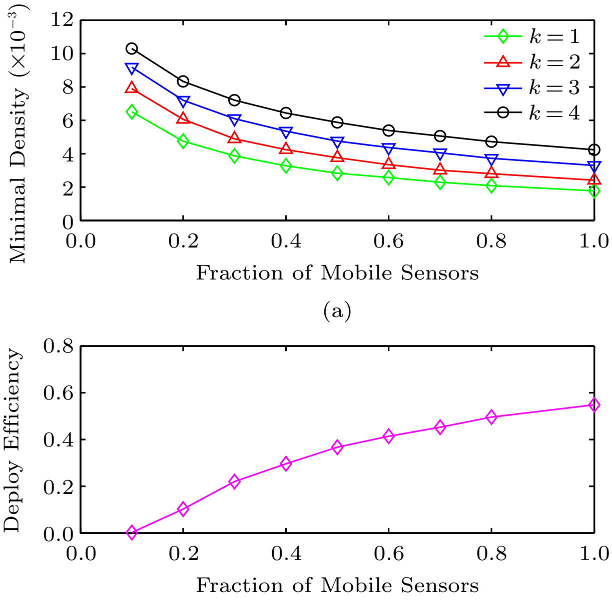


(a)

(b)

(c)

Fig.13. Probability of constructing k barriers using the proposed method in networks containing different mobile sensor fractions. (a) Fraction = 0.8. (b) Fraction = 0.4. (c) Fraction = 0.1.



(a)

(b)

Fig.14. Effect of the fraction of mobile sensors in hybrid networks. (a) Minimal deploy density. (b) Deploy efficiency.

7 Conclusions

Barrier coverage is an effective way for detecting unauthorized intrusions. It provides the required service without the need of deploying a large amount of sensors that cover the whole region. This paper focuses on the way of efficient use of deployed sensors. To this end, we proposed the distributed barrier construction scheme based on target circle (D-TarC): the ancestor senor broadcasts its most right point within its FoV and sensing radius r_s to its neighbors, and upon receiving this message, the neighbors report their energy consumption and potential barrier gain to the ancestor. Different from choosing relay sensors with maximal gain or minimum energy requirement, the ancestor chooses a node with the most profitable one as the relay sensor in terms of barrier gain and related energy consumption. Simulation results showed that it can largely reduce the wasted sensors in a random deployment, leading to an increase in barrier numbers and service time. The proposed method can also be easily adapted to hybrid networks and provide comparable quality of services with respect to existing methods.

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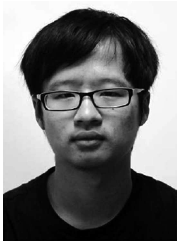

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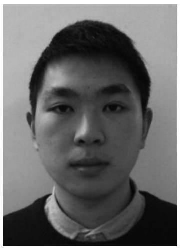

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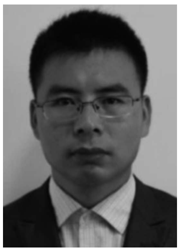

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