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Monitoring Quality Guaranteed Barrier Coverage Mechanism for Traffic Counting in Wireless Sensor Networks

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ABSTRACT Barrier coverage is one of the most important issues in wireless sensor networks. In the literature, many studies have proposed solutions to the barrier coverage problem. However, most of them discussed the traditional application which aimed for intruder detection and used the Boolean sensing model (BSM). In fact, the barrier coverage issue can be applied to the new application of traffic count. This paper proposes two barrier coverage mechanisms, which consider the new application of traffic count and applies another sensing model, called probabilistic sensing model (PSM), which assumes that the sensing probability of a sensor is a probabilistic value depending on the distance between the sensor and object. As compared to BSM, the PSM model is more practical since it considers the interference and other environmental conditions. The proposed two barrier coverage mechanisms, called (weighted based working scheduling) *WBWS* and (connectivity based working scheduling) *CBWS*, aims to reach the predefined monitoring quality of barrier boundary while satisfying the minimum numbers of sensors. Experimental study reveals that the proposed *WBWS* and *CBWS* mechanisms outperform existing related studies in terms of surveillance quality and hardware cost.

INDEX TERMS Wireless sensor networks, barrier coverage, probabilistic sensing model, surveillance quality.

I. INTRODUCTION

Wireless sensor networks (WSNs) are composed of many sensor nodes each of which supports functions including sensing, data processing, and communication. The WSNs have been widely applied in many applications, including country boundaries, battlefield surveillance, machine health monitoring, as well as environmental monitoring [6]–[22]. Network coverage is one of the most important issues in WSNs. Basically, the coverage issues can be classified into the following three categories from applications: target coverage [3], barrier coverage [4] and area coverage [3]–[5].

In literature, a large number of studies have discussed the coverage issue. Most of these studies aim to select a minimal number of sensors to be waked up while satisfying the constraint of monitoring quality. Based on the applied sensing model, these studies can be further divided into two sets: Boolean sensing model (BSM) and Probabilistic Sensing Model (PSM). The monitoring quality mainly depends on two factors: the number of working sensor and the sensing ability of each sensor. The sensing model reflects the sensing ability of a sensor, which will directly affect estimation of the barrier coverage quality. In literatures, most studies applied Boolean Sensing Model (BSM) as their sensing model. In the BSM, the sensing range of each sensor is considered as a perfect disc [7]–[22]. On the contrary, the Probabilistic Sensing Model (PSM) uses a detection probability value, ranging from 0 to 1, to represent the sensing capability of each working sensor. Though the PSM is more complicated than BSM in estimating the surveillance quality, but it matches physical sensing behaviors of most commercial sensors, as compared with the BSM.

According to the types of applications, studies related to the barrier coverage can be further divided into two categories: intruder detection [7]–[12] and traffic flow monitoring [20], [21]. In literature, most studies falling in the class of intruder detection aim to wake up as few as possible sensors monitoring the barrier such that any intruder crossing the field from one side to another will be detected by at least one sensor on the defense barrier. A defense barrier composed of a set of sensors is said to satisfy the k-barrier coverage only if any intrusion is detected by at least k distinct sensors [7]–[12]. This type of barrier reduces the possibility of missing intruders and enhances fortification and security. This problem of barrier coverage has been a topic for discussion in many literatures and studies.

Alternatively, the traffic flow detection [20], [21] is a new application of the barrier coverage which aims to wake up a minimal number of sensors but guarantees the monitoring quality of k-cover. The problem of counting traffic flow can be treated as a barrier coverage problem. Consider the scenario shown in Fig. 1 When the vehicle moves from left to right, it can be detected by sensors a, b and c. This can be considered that sensors a, b and c construct 3-barrier which can detect the vehicle three times. Since each sensor can independently detect the vehicle, the considered barrier coverage can be treated as a weak barrier coverage.

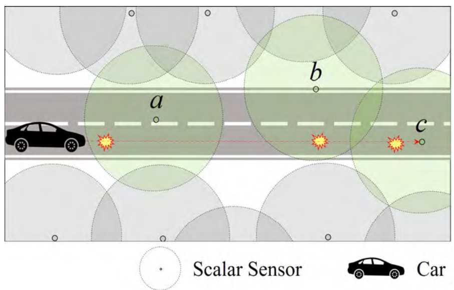


FIGURE 1. The barrier coverage issue for counting traffic flow.

In the flow detection application, the traffics of some roads should be accurately counted. Most existing mechanisms developed for traditional barrier coverage cannot support the new application such as traffic count. In the new scenario, any one sensor whose sensing range, overlapped with the road can count the number of vehicles passing through the road. To improve the accuracy, k sensors that are overlapped with the given road can support fault tolerance and improve the monitoring quality. Study [20] aims to construct k barriers by selecting a minimal number of sensors. To overcome this problem, two novel approaches are proposed to construct a k-barrier coverage while maximizing a network lifetime. Existing work [21] proposed a recovery mechanism using mobile sensor to improve the boundary segment where the k-coverage is not satisfied. However, studies [20] and [21] applied Boolean Sensing model and their performance still can be improved.

Given a set of sensors deployed along the roads, this paper proposes an efficient barrier coverage algorithm which schedules the sensors with maximal contributions to count the traffic flow. The proposed algorithm aims to guarantee the predefined accuracy while the network lifetime of wireless sensor networks can be maximized.

This paper applies PSM as the sensing model aiming to construct a barrier coverage with guaranteed quality for the new application of traffic count. Two barrier coverage mechanisms, called Weighted Based Working Scheduling (*WBWS*) and Connectivity Based Working Scheduling (*CBWS*), are proposed aiming to find as few as possible working sensors for constructing barrier which guarantees the boundary surveillance quality. One challenge of the proposing *WBWS* is to schedule the working sensors such that the predefined monitoring quality can be reached, especially when considering the sensing model of PSM. To overcome the challenge, this paper tries to find out the road segment with the weakest monitoring quality. Then one best sensor will be selected to improve the monitoring quality of this segment. In addition to the proposed *WBWS*, another barrier coverage mechanism, called *CBWS,* additionally considers the network connectivity issue which guarantees the connectivity of working sensors.

The key contributions of the proposed *WBWS* and *CBWS* are itemized as follows:

(1) **The physical characteristics of sensors are taken into consideration.** Most of previous works applied BSM to develop the barrier coverage mechanisms. The calculation of sensing probability is not accurate, causing coverage holes existed in the actual environment. This paper applies the probabilistic sensing model which better matches physical sensing behaviors and hence improves the surveillance quality as compared with existing studies [15]–[22].

(2) **The surveillance quality of traffic count is enhanced.** The scheduling algorithm allocates working sensors to improve the monitoring quality of the traffic count. The proposed *WBWS* and *CBWS* make full use of cooperative sensing between *sensors*. Compared with the existing studies [20], [21], the surveillance quality can be significantly improved.

(3) **The lifetime of Wireless sensor network is enhanced.** The scheduling algorithm allocates working sensors to reach the Predefined monitoring quality. The proposed *WBWS* and *CBWS* carefully evaluate the contribution of each sensor and select the one that creates maximal cooperative contribution to be the working sensor. Simulation results show that the proposed *WBWS* and *CBWS* select smaller number of working sensors and hence increase the network lifetime of WSNs, as compared with the existing works [20], [21].

This paper applies the probability based sensing model which can better evaluate the surveillance quality than the Boolean sensing model. Consequently, the surveillance quality can be improved, as illustrated in the first contribution. In addition, the developed algorithms consider the road with weakest surveillance quality and select the sensor with largest contribution to improve the surveillance quality of that road. This also helps improve the surveillance quality while the number of working sensors can be reduced. As a result, the second and third contributions can be achieved.

The remaining part of this paper is organized as follows. Section II introduces the related work. Section III presents the network environment and problem statement. Sections IV gives the detailed descriptions of the proposed *WBWS* and *CBWS* algorithms. Section V presents the simulation results. Finally, the conclusion and future work are drawn.

II. RELATED WORK

In recent years, a large number of barrier coverage mechanisms have been proposed. In general, these mechanisms are developed based on two sensing modes. The following reviews these studies and points out the contribution of this paper against the existing works.

A. BARRIER COVERAGE BY APPLYING BOOLEAN SENSING MODEL (BSM)

In the past few years, the barrier coverage problem has been studied extensively. Huang and Tseng [2] proposed a centralized algorithm for constructing a barrier in wireless sensors networks. Balister *et al.* [3] proposed several coverage protocols for heterogeneous sensors, each with arbitrary sensing and transmission radius. The algorithms largely reduced energy overhead while preserving coverage quality. In [6], the study firstly defined the notion of k-barrier coverage of a belt region for wireless sensors. It proposed an algorithm to determine whether a belt region supports k-barrier coverage. Liu *et al.* [7] derived critical conditions for strong barrier coverage. They proposed a distributed algorithm to construct disjoint barriers in a large sensor network to cover a long boundary area of irregular shape. Chen *et al.* [9] proposed algorithms to detect the quality of the barrier. If the quality of the barrier is below the predefined level, they further proposed a method to identify all the weak region. Then, a repaired algorithm is given for repairing the weak region until the barrier achieves a predefined level. Kumar *et al.* [15] proposed a sleep-wake-up schedule for sensors, aiming to maximize the lifetime of the barrier for wireless sensors networks. Kim *et al.* [20] proposed a new type of barrier, which can detect every movement of mobile objects on paths. Kim *et al.* [21] proposed a mechanism for repairing a failed area. If the energy of the sensors is lower than the minimum standard value, the sensors will not be able to work. The barrier will appear to be an unregulated area. They proposed a resilient event-driven partial barriers using mobile sensors, which can maintain barriers continuously as well as can repair a failed area.

Mostafaei *et al.* [23] aimed to construct as more as possible barriers and to minimize the energy consumptions of the sensors participated in a working barrier. A scheme, called distributed border surveillance (DBS), has been proposed to find minimal number of sensors to construct a barrier for prolonging the network lifetime. In DBS approach, learning automaton is assisted to find the best nodes to guarantee the barrier coverage. Wang *et al.* [24] studied the barrier coverage issue by considering the situation that some sensor nodes have location errors. The mobile sensor nodes are also considered to relocate their locations if the deployed static sensors are not barrier-covered after initial deployment. Then a fault-tolerant weighted barrier graph is proposed to model the barrier coverage problem. According to this graph, they proved that the barrier coverage can require minimum number of mobile sensors for the shortest path on the graph. Furthermore, they removed unnecessary edges on the graph to reduce the computational complexity of the proposed algorithm. Mostafaei *et al.* [25] proposed a scheduling algorithm, called ICABC, aiming for selecting sensor nodes to construct a barrier. The main objective is to extend the network lifetime. Mostafaei and Meybodi [26] proposed an energy aware scheduling method based on learning automata. Each node is equipped with a learning automation in order to select best node to guarantee barrier coverage, at any given time.

The studies mentioned above adopt Boolean Sensing Model which might not be accurate in real applications. Because the Boolean Sensing Model does not take into account the surrounding environment factors and noise. Simultaneously, Boolean Sensing Model only returns one value of coarse approximation to the practical sensing model. Because the sensing probability cannot be idealized as only 0 or 1, the sensing probability should be changed dynamically with the distance. To improve these problems and to consider the authenticity, this paper applies the PSM as our sensing model.

B. BARRIER COVERAGE BY APPLYING PROBABILISTIC SENSING MODEL (PSM)

Different from the Boolean Sensing Model, the PSM assumes that the sensing probability of an event occurred in the sensing range is not a 0 or 1 constant. Study [12] proposed two types of sensing models: Boolean sensing model and Probabilistic sensing model. They investigate the impact of sensing models on network coverage. The sensing probability is a decreasing function of the sensing distance. Compared with the BSM, the PSM is more reasonable and can reflect the complex effects of the real world. Yang and Qiao [13] studied the problem of barrier coverage with PSM. They only considered the condition for weak barrier coverage, assuming that the intruder crosses the barrier along a straight line. However, it is not suitable for emergency surveillance. Li *et al.* [14] used PSM to analyze the detection probability of arbitrary path where an intruder crosses the barrier with the maximum moving speed. Based on the theoretical analysis of detection probability, they proposed a bounded approximation algorithm. Though the abovementioned studies applied the probabilistic sensing model to achieve better results in surveillance quality, they did not consider the energy consumption of the given wireless sensor networks.

C. BARRIER COVERAGE AIMING FOR MAXIMIZING THE NETWORK LIFETIME

In literature, most studies assumed that sensors are battery powered. Chen *et al.* [16] developed a novel sleep-wake up algorithm for maximizing the network lifetime. Simultaneously, this algorithm provides close to optimal enhancement in network lifetime, while providing global barrier coverage most of the time. The algorithm divides the network environment into several blocks and proves the fact that if each block is k-barrier coverage, then the whole network is also k-barrier coverage. Chang *et al.* [17] developed a decentralized scheme to cope with the k-barrier coverage problem. It selects the appropriate sensors to construct the defense lines from left to right in a rectangle region based on the location information of sensors. Wang *et al.* [18] proposed a linear programming algorithm based on the comprehensive search of the possible barriers. Through this algorithm, the best barrier and the best schedule of sensors can be found out. Kumar *et al.* [22] developed two algorithms for barrier coverage by considering two types of sensors: with homogeneous lifetime and heterogeneous lifetime. Although the above mentioned studies have proposed many algorithms to extend the lifetime of WSNs, they did not consider the probability model.

In this paper, two algorithms, called *WBWS* and *CBWS*, are proposed to cope with the above-mentioned problems. Table I summarizes the characteristics of the previous related studies and the proposed algorithm. The proposed two algorithms consider the practical sensing model of PSM and improve the monitoring quality of road traffics. The design of the proposed two algorithms is elaborated in the next section.

TABLE 1. Main characteristics of the proposed algorithms and the related works.

Related Work	physical characteristics of the sensor	Energy Aware	Novel Application	Monitoring Quality
[2]	×	✓	×	✓
[3]	×	✓	×	×
[6]	×	✓	×	✓
[7]	×	✓	×	✓
[9]	✓	×	×	✓
[13]	✓	✓	×	×
[14]	✓	✓	×	✓
[15]	×	✓	×	×
[17]	×	✓	×	✓
[18]	×	✓	×	×
[20]	×	✓	✓	✓
[21]	×	✓	✓	✓
[22]	×	✓	×	✓
Ours	✓	✓	✓	✓

III. NETWORK ENVIRONMENT AND PROBLEM STATEMENT

Assume that the monitoring region is a rectangle region R. Let $H = \{h_1, h_2 \ldots\ldots h_u\}$ denote the set of u cities located in region R. Let $L = \{l_1, l_2 \ldots\ldots l_x\}$ denote the set of x disjoint roads in region R. Each road l_i connects two cities and each pair of two cities might exist several disjoint roads. A set of n sensors $S = \{s_1, s_2, s_3 \ldots\ldots s_n\}$ is randomly deployed in R for monitoring vehicles traffics. Assume each sensor s_i has an unique ID and is aware of its own location (x_i, y_i). Each sensor also knows the IDs and locations of its neighbors through message exchanges with neighboring sensors. Also, we assumed that the times of all sensors are synchronous. Let r_s and r_t denote the sensing radius and transmission radius of each sensor, respectively. In addition, the communication radius is at least twice the sensing radius. That is, we have $r_t \geq 2r_s$.

Figure 2 give an example where four cities are existed in region R. Roads l_3 and l_4 connect the pair of cities h_1 and h_3. Many sensors are randomly deploying in region R. To make it clear, only those sensors that are intersecting with roads l_3 and l_4 are displayed in Fig. 2.

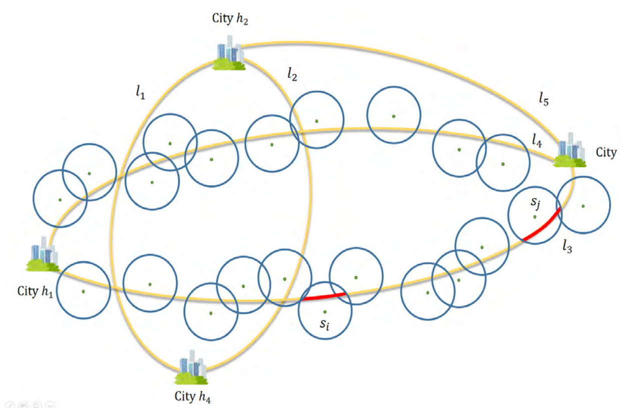


FIGURE 2. An example of the investigated WSNs.

A. SENSING MODEL

This section introduces the sensing model applied in this paper. There are two sensing models that have been widely applied in previous studies. The first one is the Boolean sensing model which assumes that the sensing range of each sensor is a perfect disc. An event can be detected by the sensor if and only if it occurs in the sensing range. As a result, there are only two results for sensor detection: detected or not detected. In literature, most studies related to barrier coverage applied the Boolean Sensing Model (BSM). Though the Boolean sensing model is simple, it is not practical.

Fig. 3 depicts two sensing models. As shown in Fig. 3 (a), the BSM is only a coarse approximation to the practical sensing model. Unlike the BSM, the Probabilistic Sensing Model (PSM), as shown in Fig. 3 (b), further assumes that the sensing ability of a sensor is a decreasing function of the distance between the sensor and the event location. Though PSM is more complicated than BSM in estimating the surveillance quality, the PSM is actually more practical than BSM since the physical sensing behaviors of most commercial sensors match PSM better. It is still a big gap between the practical performance and the performance of the existing barrier coverage algorithms which apply the BSM.

As shown in Fig. 3 (b), the yellow region indicates that the sensing range is dynamically changed with several environmental parameters and is not a perfect disc. The PSM divides the sensing area into guaranteed sensing area and uncertain sensing area. The guaranteed sensing area is the region inside

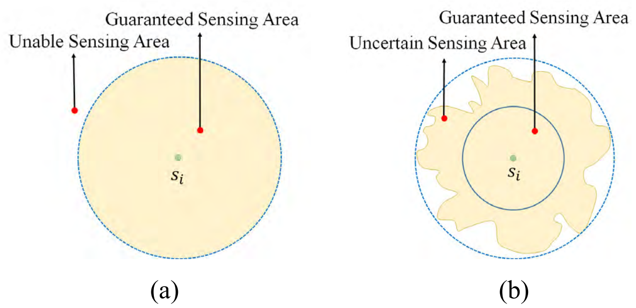


FIGURE 3. **Two sensing models. (a) BSM. (b) PSM.**

the solid circle. On the contrary, the uncertain sensing area is the region outside the blue solid line and inside blue dash line. Fig. 4 further explains the PSM in a conceptual level. Consider Fig. 4. The dotted circle represents the possible sensing range while the solid circle represents the guaranteed sensing area. Let r_s^g and r_s denote the radiuses of the solid and dotted circles, respectively.

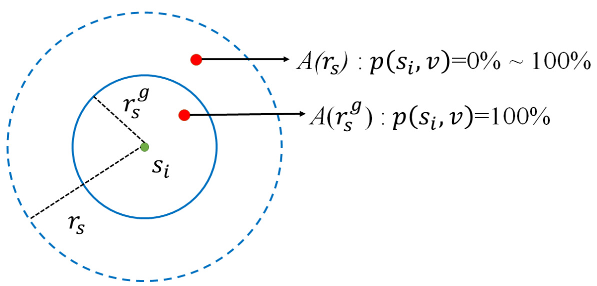


FIGURE 4. **This is PSM, and the probability of sensing in regions $A(r_s^g)$ and $A(r_s)$ are 100% and 0% ∼ 100%.**

Let A(r_s) denote the circle area spanned by the radius r_s. As shown in Fig. 4, if the event occurs at a location in region $A(r_s^g)$, the event can be detected by sensor s_i with a probability of 100%. However, if the event occurs at a location in region $A(r_s)$-$A(r_s^g)$, the event can be detected by sensor s_i with a probability ranging from 0% to 100%, depending the distance between the locations of event and sensor s_i.

Consider an event occurred at the point v and the coordinates of point v are (x_v, y_v). Let $p\,(s_i, v)$ denote the probability of sensor s_i sensing to point v, and $d\,(s_i, v)$ denote the distance between sensor s_i and point v. The following expression represents the relationship between the sensing probability p and the distance d.

$$p\,(s_i, v) = \begin{cases} 1, & d\,(s_i, v) \le r_s^g \\ e^{-\lambda(d(s_i,v)-r_s^g)^{\gamma}}, & r_s^g < d\,(s_i, v) < r_s \\ 0, & d\,(s_i, v) \ge r_s \end{cases} \tag{1}$$

In Exp. (1) the parameters λ and γ are the road loss exponent of the sensing signal strength and they are adjusted according to the physical properties of sensor. The distance $d\,(s_i, v)$ can be calculated by the Exp. (2).

$$d\,(s_i, v) = \sqrt{(x_i - x_v)^2 + (y_i - y_v)^2} \tag{2}$$

This paper applies the PSM sensing model to investigate the barrier coverage problem which concerns the issue of traffics monitoring.

B. PROBLEM FORMULATION

This study aims to guarantee the traffic monitoring quality of each road and minimize the number of working sensors. Let ρ denote the predefined requirement of surveillance quality of each road. A scheduling algorithm, say Λ, aims to take S, L and H as its inputs and then determine a set $\hat{S} = \{\hat{s}_1, \hat{s}_2, \ldots\ldots \hat{s}_{\hat{n}}\}$, $\hat{S} \subset S$ of $\hat{n}$ working sensors such that their contributions in terms of surveillance quality can meet the requirement ρ. Let notation $q_i(\hat{S})$ denote the monitoring quality of road l_i providing that the set of working sensor is $\hat{S}$. Exp. (3) presents the monitoring quality constraint.

1) MONITORING QUALITY CONSTRAINT

$$q_i(\hat{S}) \ge \rho, \quad \hat{S} \subset S, \quad \forall i \in x \tag{3}$$

There are three states for each sensor: sensing, transmission and sleeping states. Let Boolean variables γ_i^{sen}, γ_i^{tra} and γ_i^{slp} denote that sensor s_i stays in sensing, transmission and sleeping states, respectively. That is

$$\begin{aligned} \gamma_i^{sen} &= \left\{\begin{matrix} 1, & \text{if } s_i \text{ is sensing now} \\ 0, & \text{otherwise} \end{matrix}\right\} \\ \gamma_i^{tra} &= \left\{\begin{matrix} 1, & \text{if } s_i \text{ is transporting now} \\ 0, & \text{otherwise} \end{matrix}\right\} \\ \gamma_i^{slp} &= \left\{\begin{matrix} 1, & \text{if } s_i \text{ is sleeping now} \\ 0, & \text{otherwise} \end{matrix}\right\} \end{aligned} \tag{4}$$

The working state constraint restrict that each sensor can stay on one state at any given time.

2) WORKING STATE CONSTRAINT

$$\gamma_i^{sen} + \gamma_i^{tra} + \gamma_i^{slp} = 1 \tag{5}$$

Let T denote the period of the time required for monitoring barrier boundary. Recall that the time can be partitioned into several time units with equal length. Let t denote any time unit. To measure the energy consumption of each sensor, the following defines some notations. Let e_t^{sec} and e_t^{tra} denote the energy consumptions of any sensor staying at sensing and transmission for a time unit, respectively. Let e_i^{rem} denote the remaining energy of sensor s_i. Exp. (6) reflects the constraint that the remaining energy of each working sensor should be large enough to support the energy required for time period T.

3) SENSOR ENERGY CONSTRAINT

$$e_i^{rem} \ge \frac{T}{t} \times (e_t^{sec} + e_t^{\mathrm{tra}}), \quad \forall i \tag{6}$$

Two sensors are said to be neighbors if they are located in the communication range of each other. Sensors s_i and s_j are said to be connected if there is a path starting from sensor s_i

TABLE 2. Notation table.

Notation	Descriptions
$H = \{h_1, h_2 \ldots h_u\}$	The set of u cities
$L = \{l_1, l_2 \ldots l_x\}$	The set of x disjoint roads
$S = \{s_1, s_2 \ldots s_n\}$	The set of n sensors
$\hat{S} = \{\hat{s}_1, \hat{s}_2 \ldots \hat{s}_{\hat{n}}\}$	The set of $\hat{n}$ working sensors
$\tilde{S} = \{\tilde{s}_1, \tilde{s}_2 \ldots \tilde{s}_{\tilde{n}}\}$	The set of $\tilde{n}$ sleeping sensors
r_s^g	The radius of the guaranteed sensing range
r_s	The radius of the uncertain sensing range
$A(r_s^g)$	The circle area spanned by radius r_s^g
q_j	The monitoring quality of road l_j.
ρ	The predefined requirement of surveillance quality of each road.
$\gamma_i^{sen}, \gamma_i^{tra}, \gamma_i^{slp}$	The states of sensor s_i. The state might be sensing, transmission or sleeping.
T	The time period for monitoring barrier boundary.
e_t^{sec}, e_t^{tra}	Energy consumptions for sensor staying at sensing or transmission states for a time unit.
e_i^{rem}	The remaining energy of sensor s_i
l_j^i	The segment of road l_j
$v_{i,closest}^j$	The point on l_j^i that is closest to sensor s_i
c_i^j	The contribution of sensor s_i on road l_j
l^{weak}	The road with weakest monitoring quality
$\tilde{S}^{weak}$	The set of sensors that cover road l^{weak}.
$q_i^{weak.new}$	The monitoring quality of road l^{weak}
w_i^{weak}	The weight of the sensor s_i on road l^{weak}.
s_{best}^{weak}	The sensor with the highest weight value on road l^{weak}.
λ_j	A Boolean variable which presents whether or not the monitoring quality of current q_j has reached the predefined value ρ.

through a finite sequence of edges which connect a sequence of neighboring nodes and finally ending at node s_j.

The set $\hat{S}$ of working sensors is said to be connected to the sink s_0 if there exists at least one communication road from any sensor s_i to s_0 and is denoted by $\hat{S}$ connect = true. Exp. (7) presents the connected constraint of a given wireless sensor network.

4) CONNECTED CONSTRAINT

Sensors s_i and s_j are connected, for all $s_i, s_j \in \hat{S}$.

This paper aims to minimize the number of working sensors while all constraints mentioned above are satisfied. Exp. (7) represents the objectives of this paper.

$$Objective: \; Minimize(\hat{n}) \tag{7}$$

The following section will present an algorithm which aims to achieve our object function given in Exp. (7), while satisfying all the constraint.

IV. THE PROPOSED ALGORITHM

The application considered in this paper is traffic monitoring which monitors the traffic of each road and reports the traffic to the sink node. This paper proposed two scheduling mechanisms to enhance the quality of traffic monitoring. To simplify the scheduling problem, the first algorithm, called *Weighted Based Working Scheduling* or *WBWS* in short, is presented by discarding the communication factor. That is, the proposed *WBWS* only focuses on the sensing quality without considering the network connectivity issue. The proposed *WBWS* not only guarantees the traffic monitoring quality of each road, but also uses the minimal number of working sensors for energy conservation. Based on the *WBWS*, the second algorithm, called *Connectivity Based Working Scheduling* or *CBWS* in short, further takes the network connectivity into consideration and allows the traffic monitoring information to be delivered to the sink node. The following presents the details of the proposed two scheduling mechanisms.

A. WEIGHTED BASED WORKING SCHEDULING (WBWS)

The *Weighted Based Working Scheduling* mainly consists of two phases, including *Sensor Contribution Evaluation Phase* and *Scheduling Phase*. The*Sensor Contribution Evaluation Phase* aims to calculate the contribution of each sensor. The *Scheduling Phase*, further measures the traffic monitoring quality of each road and schedules the sensors with larger contributions as the working sensors such that the predefined monitoring quality can be achieved while the number of working sensors can be as small as possible.

B. SENSOR CONTRIBUTION EVALUATION PHASE

The *Sensor Contribution Evaluation phase* aims to evaluate the contribution of each sensor. Fig. 5 depicts the considered scenario. As shown in Fig. 5, the road l_j connects cities h_x and h_y. A set of n sensors $S = \{s_1, s_2, s_3 \ldots\ldots s_n\}$ are deployed around road l_j aiming to monitoring the traffic of road l_j.

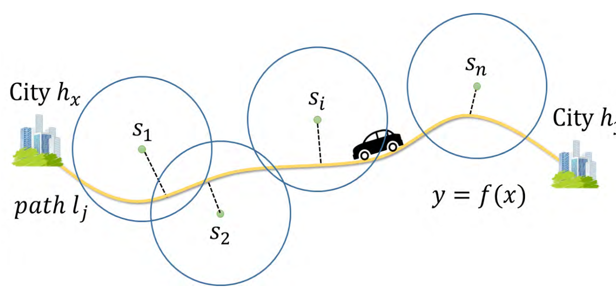


FIGURE 5. A scenario of basic contribution evaluation phase.

Herein, we notice that the probabilistic sensing model as shown in Exp. (1) is applied in this scenario. The detection probability is decreased with the distance between the sensor and the vehicle. Recall that notation $p(s_i, v)$ denotes the probability of vehicle v detected by sensor s_i. Let segment l_j^i denote the segment of road l_j that is covered by sensor s_i. Let $v_{i,closest}^j$ denote the point on l_j^i that is closest to sensor s_i. The point $v_{i,closest}^j$ would be selected as an representative point to calculated the contribution of sensor s_i to road l_j.

Let c_i^j denote the contribution of sensor s_i on road l_j. Exp. (8) gives the evaluation the value of c_i^j.

$$c_j^i = \begin{cases} 1, & d\left(s_i, v_{i,closest}^j\right) \le r_s^g \\ e^{-\lambda\left(d(s_i,v)-r_s^g\right)^\gamma}, & r_s^g < d\left(s_i, v_{i,closest}^j\right) < r_s \\ 0, & d\left(s_i, v_{i,closest}^j\right) \ge r_s \end{cases} \quad (8)$$

for each $v_{i,closest}^j \in l_j$.

In the next phase, the contribution can be used to calculate the monitoring quality for each road.

C. SCHEDULING PHASE

This phase aims to determine the set of working sensor $\hat{S}$. The proposed *WBWS* algorithm is executed in a round by round manner. Initially, all sensors are assumed in the sleep mode. In each round, one sensor that has maximal contribution to the road segment with the lowest monitoring quality will be determined to play the role of working sensor and switch to working mode. The execution of *WBWS* algorithm will be finished if the monitoring quality of each road is larger than the predefined quality. The scheduling phase mainly consists of three tasks. The first task aims to identify the road, say l^{weak}, with the weakest monitoring quality. Then the second task determines one best sensor that covers the road segment l^{weak} as working sensor. The third task checks if the monitoring quality satisfies the predefined quality. The proposed *WBWS* should be finished if it is the case. The following presents the details of each task.

Task I (Finding the Road Segment With the Weakest Monitoring Quality: This task aims to calculate the monitoring quality of each road. Recall that set $\hat{S} = \{\hat{s}_1, \hat{s}_2, \hat{s}_3 \ldots\ldots \hat{s}_{\hat{n}}\}$ denote the set of working sensors. Let $\tilde{S} = \{\tilde{s}_1, \tilde{s}_2, \tilde{s}_3 \ldots\ldots \tilde{s}_{\tilde{n}}\} \in \hat{S}$ denote the set of sleeping sensors. Let $\hat{S}^j = \{\hat{s}_1, \hat{s}_2, \hat{s}_3 \ldots\ldots \hat{s}_{\hat{n}}\} \in \hat{S}$ denote the set of working sensors for monitoring road l_j. For any sensor $\hat{s}_i \in \hat{S}^j$, the probability that sensor $\hat{s}_i \in \hat{S}^j$ cannot detect a passing vehicle is $1 - c_i^j$.

The probability that all sensors $s_i \in \hat{S}^j$ cooperatively monitor road l_j but still unable to detect the event is:

$$\prod\nolimits_{s_i \in \hat{S}^j} \left(1 - c_i^j\right). \quad (9)$$

Let q_j denote the monitoring quality of road l_j. The value of q_j can be calculated using the contributions of all working sensors $s_i \in \hat{S}^j$ as shown in Exp. (10).

$$q_j = 1 - \prod_{s_i \in \hat{S}^j} \left(1 - c_i^j\right) \quad (10)$$

The sink node will evaluate the contribution q_j for each road l_j. Let l^{weak} denote the road with weakest monitoring quality. The l^{weak} can be identified by applying the following Exp. (11).

$$l^{weak} = \arg \underset{1 \le j \le x}{min}\, q_j \quad (11)$$

According from Exp. (11), the proposed *WBWS* has identified the road with weakest monitoring quality. The next task will find one best sensor to improve the monitoring quality of this road.

Task II (Determining One Sensor as Working Sensor): Let $\tilde{S}^{weak}$ denote the set of sensors that cover road l^{weak}. This task aims to find one more sensor to play the role of working sensor according to the contribution. It is obvious that the sensor with maximal contribution will be the best one if the monitoring quality of road l^{weak} still not exceeds the predefined quality. To identify the best sensor, a weight value is defined to measure how well of the sensor contribute to the road l^{weak}. Let $q_i^{weak.new}$ denote the monitoring quality of road l^{weak} when sensor $s_i \in \tilde{S}^{weak}$ has participated in the monitoring task. The value of $q_i^{weak.new}$ can be evaluated by applying Exp. (12).

$$q_i^{weak.new} = 1 - \left\{\left(1 - q_j\right)\left(1 - c_i^j\right)\right\}, \quad s_i \in \tilde{S}^{weak} \quad (12)$$

In Exp. (13), notation w_i^{weak} denotes the weight of sensor s_i which monitors the road with weakest monitoring quality. The participation of sensor s_i might lead to the situation that the monitoring quality has larger than the required quality. The exceeded value can be expressed by expression $q_i^{weak.new} - \rho$. Since we expect the exceeded value can be as small as possible, the weight of sensor s_i should be decreased with the exceeded value. Exp. (13) exhibits the design which matches our expectation that the sensor s_i which leads to a larger value of exceeded value of road quality will have a smaller weight. On the contrary, if the participation of sensor s_i still cannot satisfy the quality requirement, the contribution of sensor s_i can be measured by expression $\left(q_i^{weak.new} - \rho\right)$. That is, sensor s_i will have a larger weight if it has larger contribution to the road quality. Exp. (14) aims to select the sensor that has the maximal weight to be the working sensor.

$$w_i^{weak} = \begin{cases} \dfrac{\rho}{1 + q_i^{weak.new} - \rho}, & q_i^{weak.new} \ge \rho \\ \left(q_i^{weak.new} - \rho\right), & q_i^{weak.new} < \rho \end{cases} \quad (13)$$

Exp. (14) aims to select the sensor that has the maximal weight to be the working sensor. When the weights of all sensor are obtained, the sensor with the highest weight would be selected as the working sensor. Let s_{best}^{weak} denote the sensor with the highest weight value for road l^{weak}. The best sensor s_{best}^{weak} can be obtained by applying Exp. (14).

$$s_{best}^{weak} = \underset{\forall s_i \in \tilde{S}}{arg\ max}\, w_i^{weak} \quad (14)$$

Then the sensor s_{best}^{weak} will move from sleeping set $\tilde{S}$ to the set of working sensors of road l^{weak} and change its state from sleep to working. These operations are done by applying Exps. (15) and (16).

$$\hat{S} = \hat{S} \cup \left\{s_{best}^{weak}\right\} \quad (15)$$

$$\tilde{S} = \tilde{S} / \left\{s_{best}^{weak}\right\} \quad (16)$$

The monitoring quality q_j will be recalculated when the sensor s_{best}^{weak} stays in working state. The contribution of sensor s_{best}^{weak} to road q_j can be calculated by Exp. (17).

$$q_j = 1 - \left\{ \left(1 - q_j\right) \left(1 - c_i^j\right) \right\}, \quad s_i \in \tilde{S}^{weak} \tag{17}$$

Task III (Checks If the Monitoring Quality Satisfies the Predefined Quality): Let λ_j denote the Boolean value which represents whether or not the monitoring quality of current q_j has reached the predefined value ρ. That is,

$$\lambda_j = \begin{cases} 1, & q_j \geq \rho \\ 0, & q_j < \rho, \end{cases} \quad 1 \leq j \leq x \tag{18}$$

Then the following condition will be checked.

$$\prod_{j=1}^{x} \lambda_j = 1 \tag{19}$$

If the monitoring quality of all roads were larger than ρ, the proposed *WBWS* will be terminated.

Figure 6 summarizes the operations designed in *WBWS* algorithm.

D. CONNECTIVITY BASED WORKING SCHEDULING (CBWS)

Recall that the proposed *WBWS* aims to select some working sensors to monitor the traffic quality of each road. However, the working sensors might not be connected, different from the *WBWS*, the main goal of *CBWS* aims to guarantee that all the working sensors are connected.

The *Connectivity Based Working Scheduling* mainly consists of two phases, including *Contribution Evaluation Phase* and *Connection Based Scheduling Phase*. The *Sensor Contribution Evaluation Phase* aims to calculate the contribution of each sensor. The calculation of contribution is omitted herein since it is similar with that in *WBWS*. The *Connection Based Scheduling Phase*, further determines the working sensor based on the following two criteria. The first issue is that the contribution of the sensor to the monitoring quality of the associated road. The second issue for determining the working sensor is the demand of connection. That is, the new working sensor should be connected to the sensors that have already stayed in working state.

The proposed Connection Based Scheduling Phase aims to determine a set of working sensors $\hat{S}$ such that the predefined monitoring quality can be achieved while the number of working sensors can be as small as possible. This phase is generally a loop-based algorithm where one best working sensor will be selected from the sensors in sleeping mode in each loop and the loops will be finished until the predefined monitoring quality is reached. Initially, it is assumed that all sensors stay in the sleep mode. The process of selecting best sensor is similar with that in the *WBWS* algorithm. The major difference is that the selected sensor should be connected with the sensors that have been already selected. Fig. 7 depicts the considered scenario.

Weighted Based Working Scheduling(*WBWS*) algorithm	
Input:	
1. A set of sensors $S = \{s_1, s_2 \ldots \ldots s_n\}$. A set of x road $L = \{l_1, l_2 \ldots \ldots l_x\}$. A set of m cities $H = \{h_1, h_2 \ldots \ldots h_m\}$.	
2. The predefined requirement of surveillance quality ρ.	
Output:	
1. The number of working sensors set $\hat{S}$.	
Phase 1	***Sensor Contribution Evaluation Phase***
	/*Calculate the contribution of the sensor*/
	for($j = 1, j \leq n, j++$){
	for($i = 1, i \leq x, i++$){
	$c_j^i = \max p(s_i, v_{i,closest}^j), v \in l_j$;
	};
	};
Phase 2	***Scheduling Phase***
	/* Calculate the monitoring quality of each road. */
	$satisfied = false$;
	while(not $satisfied$)){
	$q_j = 1 - \prod_{s_i \in \hat{S}^j}(1 - c_i^j)$;
	$l^{weak} = arg \min_{1 \leq j \leq x} q_j$;
	/*Let $q_i^{weak.new}$ denote the monitoring quality of road l^{weak} when sensor $s_i \in \tilde{S}^{weak}$ has participated in the monitoring task. */
	for($i = 1, i \leq n, i++$){
	$q_i^{weak.new} = 1 - \{(1 - q_j)(1 - c_i^j)\}, s_i \in \tilde{S}^{weak}$;
	if ($q_i^{weak.new} \geq \rho$){
	$w_i^{weak} = \frac{\rho}{1 + q_i^{weak.new} - \rho}$;
	};
	else{
	$w_i^{weak} = (q_i^{weak.new} - \rho)$
	};
	};
	$s_{best}^{weak} = arg\,max_{\forall s_i \in \tilde{S}}\, w_i^{weak}$;
	$\hat{S} = \hat{S} \cup \{s_{best}^{weak}\}$;
	$\tilde{S} = \tilde{S} \,/\, \{s_{best}^{weak}\}$;
	$q_j = 1 - \{(1 - q_j)(1 - c_i^j)\}, s_i \in \hat{S}^{weak}$;
	if ($q_j \geq \rho$){
	$\lambda_j = 1$;
	}
	else
	$\lambda_j = 0$;
	if ($\prod_{j=1}^{x} \lambda_j = 1$) *satisfied*=true;
	};
	/* Calculate the monitoring quality of each road. */

FIGURE 6. The propose of the ***WBWS*** algorithm.

To ensure that all sensors are connected to the sink node, the first selected sensor would be the sink node. As shown in Fig. 7, sensor s_0 is the sink node. At the start of each loop,

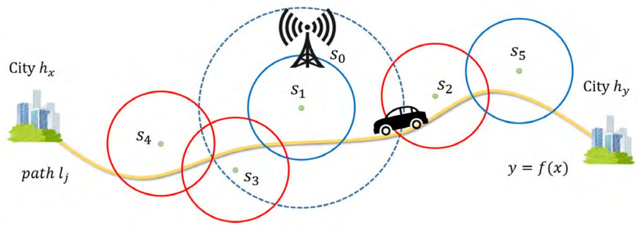


FIGURE 7. An example of ***CBWS***.

a candidate set will be determined which is formed by those sensors that stay in sleeping mode but connect to those sensors that have been selected as the working sensors. In the first loop, since there is only sensor s_1 connecting sink node, the candidate set is $\{s_1\}$ and sensor s_1 will be selected as the working sensor. That is, $\hat{S} = \{s_1\}$. In the second loop, the candidate set is s_2, s_3, s_4 since these sensors connect to s_1. By applying Equs. (9), (10) and (11), the road with weakest monitoring quality can be identified. Fig. 7 simplifies the complexity of the example by considering only one road. The next operation is to further apply Equs. (12) and (13) for evaluating the contribution and weight of each sensor in the candidate set, respectively. After that, Equ. (14) will be applied for selecting the best sensor to stay in the working state. As a result, the sensor s_3 will be selected. The above mentioned process will be repeated applied until that the monitoring quality has reached the predefined monitoring quality.

The following formally presents the operations designed in Phase 2. Let $\hat{S}^j$ and S^j denote the sets of sensors on road l_j that stay in working and sleeping modes, respectively. Initially, we have $\hat{S}^j = \emptyset$ and $S^j = \{s_1, s_2, \ldots, s_n\}$. Let $S^{\text{candidate}}$ denote the set of sensors that are connected to at least one sensor in $\hat{S}^j$. The phase 2 is a loop based design where each loop will determine one best sensor to act as the working sensor. In each loop, the $S^{\text{candidate}}$ will be firstly constructed. Then Equs. (12) and (13) will be further applied to evaluate the contribution and weight of each sensor in $S^{\text{candidate}}$, respectively. After that, the following Exp. (20) will be applied to select the best sensor s_{best}^{weak} as the working sensor.

$$s_{best}^{weak} = arg \max_{\forall s_i \in S^{\text{candidate}}} w_i^{weak} \tag{20}$$

Then the sensor s_{best}^{weak} will move from candidate set $S^{\text{candidate}}$, to the set $\hat{S}^j$ and change its state from sleeping to working, as shown in Exps. (21), (22) and (23), respectively.

$$\hat{S}^j = \hat{S}^j \cup \left\{ s_{best}^{weak} \right\}, \quad s_{best}^{weak} \in S^{\text{candidate}} \tag{21}$$

$$S^{\text{candidate}} = S^{\text{candidate}} / \left\{ s_{best}^{weak} \right\} \tag{22}$$

$$S^j = S^j / \left\{ s_{best}^{weak} \right\} \tag{23}$$

The monitoring quality will be recalculated when the sensor s_{best}^{weak} changes its state from sleep to working. The monitoring quality of the road l^{weak} is calculated by applying Equ. (17).

Equs. (18) and (19) will be further applied to check if all roads are satisfied with the predefined monitoring quality. If it is the case, the loop will be terminated.

The following presents the *CBWS* algorithm.

The following analyzes the computational complexities of the proposed two algorithms. In the proposed *WBWS*, there are two phases. The first phase aims to evaluate the contribution of each sensor. To achieve this, two for-loops are operated. The first loop is performed n times while the second loop is performed x time. Therefore, the computational time complexity of Phase one is $O(nx)$. The goal of the second phase is to select some sensors with larger contributions to be the working sensors. The execution of the second phase consists of steps 7-33. The major computations are counted below. In step 9, the worst case of the while-loop will be performed by n times, causing complexity to be $O(n)$. The condition of while-loop can be determined by $O(x)$. Therefore, step 9 requires $O(nx)$. Inside the while-loop, complexities of steps 10 and 11 are $O(x)$. The complexity of step 22 is $O(n)$ in the worst case. A for-loop in Step 13 creates a complexity of $O(n)$. As a result, the complexity of the second phase is $O(n(3x + n))$=$O(n^2 + 3xn)$. Putting complexities of Phases 1 and 2 together, the complexity of the proposed *WBWS* is $O(max(n^2, xn))$. In general, the number of sensors is much larger than the number of roads. Consequently, the complexity of WBWS can be simplified as $O(n^2)$. The algorithm *CBWS* is similar to *WBWS*. The complexity of *CBWS* is $O(n^2)$.

V. SIMULATION

This section studies the performances of the proposed mechanisms *Weighted Based Working Scheduling* (*WBWS*) and *Connectivity Based Working Scheduling* (*CBWS*) against the existing*Greedy Shared Barrier* (*GSB*) and *Greedy Shared Sensor* (*GSS*) [20]. The existing GSS and GSB mainly apply Boolean Sensing Model which causes inaccurate detection, as compared with the probabilistic sensing model which is applied by our algorithms. In addition, the existing GSS selects the sensor which can simultaneously monitor more than one road. Similar to GSS, the GSB selects the sensors belonging to the barrier which can simultaneously monitor more than one road. The performances of the four compared algorithms are evaluated in terms of the network lifetime, energy consumption, fairness index as well as efficiency index. The MATLAB simulator is used as the simulation tool.

The following illustrates the arranged simulation environment. The sensor nodes are randomly deployed in the monitoring area which contains several roads. The area size is 300 m × 300 m while the number of sensors is ranging from 150 to 300. The initial energy of each sensor node is 100 J. All sensors are connected. The sensing and communication ranges of each sensor node are set at 20 m and 40 m, respectively. Each sensor node generates one data packet and will send it to the base station in each round. Each node is aware of its own location and the sink's location.

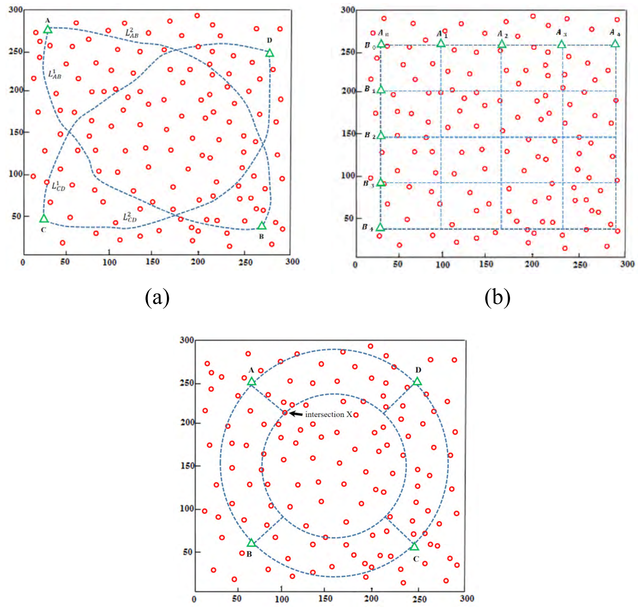
Connectivity Based Working Scheduling(*CBWS*)Algorithm	
Inputs: A set of n sensors $S = \{s_1, s_2, s_3 \dots \dots s_n\}$. A set of x road $L = \{l_1, l_2 \dots \dots l_x\}$. A set of u cities $H = \{h_1, h_2 \dots \dots h_u\}$. The predefined requirement of surveillance quality ρ.	
Output: The number of working sensors set $\hat{S}$	
Phase 1	***Sensor Contribution Evaluation Phase***
	/*Calculate the contribution of the sensor*/
	for($j = 1, j \leq n, j++$){
	for($i = 1, i \leq x, i++$){
	$c_j^i = \max p(s_i, v_j^i), v \in l_j$;
	};
	};
Phase 2	***Scheduling Phase***
	/* Calculate the monitoring quality of each road. */
	$satisfied = false$;
	while(not $satisfied$)){
	$q_j = 1 - \prod_{s_i \in \hat{S}^j}(1 - c_i^j)$;
	$l^{weak} = arg \min_{\forall j \in x} q_j$;
	/*Let $q_i^{weak.new}$ denote the monitoring quality of road l^{weak} when sensor $s_i \in S^{candidate}$ has participated in the monitoring task. */
	for($i = 1, i \leq$ n$, i++$){
	$q_i^{weak.new} = 1 - \{(1 - q_j)(1 - c_i^j)\}, s_i \in S^{candidate}$;
	if ($q_i^{weak.new} \geq \rho$){
	$w_i^{weak} = \frac{\rho}{1 + q_i^{weak.new} - \rho}$;
	};
	else{
	$w_i^{weak} = (q_i^{weak.new} - \rho)$;
	};
	};
	$s_{best}^{weak} = arg \max_{\forall s_i \in S^{candidate}} w_i^{weak}$;
	$\hat{S}^j = \hat{S}^j \cup \{s_{best}^{weak}\}, s_{best}^{weak} \in S^{candidate}$;
	$S^{candidate} = S^{candidate} / \{s_{best}^{weak}\}$;
	$S^j = S^j / \{s_{best}^{weak}\}$;
	$S^j = S^j / \{s_{best}^{weak}\}$;
	$q_j = 1 - \{(1 - q_j)(1 - c_i^j)\}, s_i \in \hat{S}^{weak}$;
	if ($q_j \geq \rho$){
	$\lambda_j = 1$;
	};
	else
	$\lambda_j = 0$;
	if ($\prod_{j=1}^{x} \lambda_j = 1$) *satisfied*=true;
	};

FIGURE 8. The propose of the ***CBWS*** algorithm.

Three scenarios, including Organic Pattern Network (OPN), Grill Network (GN) and Radial Type Network (RTN), are considered in the experiments, as shown in

TABLE 3. Simulation setting.

Parameter	Value
Simulator	Matlab
Node deployment	Random
Given Region	300*300
The number of sensor node	150-300
Sensor node transmission range	20m-40m
Consumed energy in transmitter circuit	0.18J
Consumed energy at the receiver circuit	0.1J



(a) (b) (c)

FIGURE 9. Three scenarios considered in the experiments. (a) OPN scenario. (b) GN scenario. (c) RTN scenario.

Figs. 9(a), 9 (b) and 9 (c), respectively. In Fig. 9, the green triangles represent the cities, the blue lines represent the roads and red circle represents the sensors.

The sensors whose sensing ranges cover the roads can periodically report to the sink node the number of vehicles it has scanned. Fig. 9 (a) depicts the OPN scenario which has four cities, A, B, C, and D. Both the roads L_{AB}^1 and L_{AB}^2 connect cities A and B while roads L_{CD}^1 and L_{CD}^2 connect cities C and D. As shown in Fig. 9 (b), the second scenario, called GN, contains five vertical roads and five horizontal roads. The i-th vertical road is labeled with A_i and the j-th horizontal road is labeled with B_j. As shown in Fig. 9 (c), the RTN scenario consists of two rings. Each ring is a circular road and there are four bridges connecting the two rings.

Fig. 10 compares the performance of the four algorithms in terms of the number of working sensors. The number of deployed sensors varies from 150 to 300. Three scenarios given in Fig. 10 are considered. In comparison, the proposed *WBWS* and *CBWS* have better performance than existing mechanisms *GSS* and *GSB* in all cases. The algorithms of *GSS* and *GSB* prioritizes selecting the sensor that can monitor

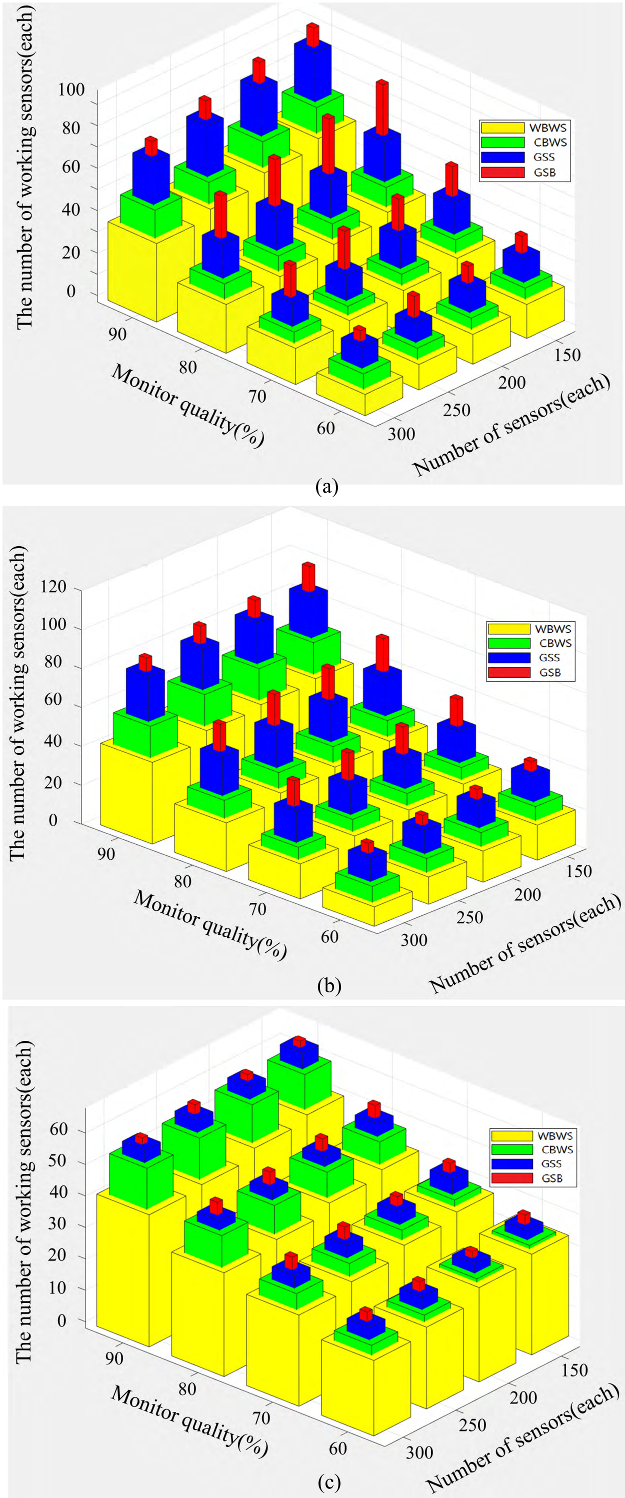


FIGURE 10. **(a) The comparisons of four algorithms in terms of the numbers of working sensors in OPN scenario. (b) The comparisons of four algorithms in terms of the numbers of working sensors in GN scenario. (c) The comparisons of four algorithms in terms of the numbers of working sensors in RTN scenario.**

multiple roads simultaneously. They can likely maximize the network lifetime by minimizing the number of sensors. However, as shown in Fig 10 (a), the intersection in the OPN scenario is very rarely between the two cities. Therefore, the good property of *GSS* and *GSB* algorithms cannot be fully utilized. On the contrary, the proposed algorithms *WBWS* and *CBWS* prioritizes selecting the sensor which contributes the highest monitor quality to each road. Moreover, the proposed *WBWS* and *CBWS* applies PSM as their sensing model, which obtains more accurate monitoring qualities. As a result, the proposed *WBWS* and *CBWS* have better performance than existing *GSS* and *GSB* in terms of the number of working sensors. In particular, the number of working sensors decreased with the number of deployed sensors. This occurs because that more sensors can be selected when the number of deployed sensors increases.

Fig. 10 (b) compares the four algorithms using GN Scenario. One major characteristic in GN scenario is that there are many intersections between roads. This characteristic helps improve the performances of *GSS* and *GSB*, as compared with the performances using OPN scenario. The proposed *WBWS* and *CBWS* algorithms need to wake up more sensors to reach the predefined monitoring quality, as compared with the OPN scenario. In comparison, the proposed *WBWS* and *CBWS* algorithms have less number of working sensors than *GSS* and *GSB*. This occurs because that the proposed algorithms prior selects the sensor with larger contribution to be the working sensor.

Fig. 10 (c) compare the four algorithms using the RTN scenario which consists of two rings. In the RTN scenario, each ring is a circular road and there are four bridges connecting the two rings. The sensors closed to the intersection can simultaneously contribute the monitoring qualities of different roads. For example, sensors closed to intersection X have contributions to roads AC and BD at the same time. As a results, the four algorithms have better performance in RTN scenario than in OPN and GN scenarios. In comparison, the proposed *WBWS* and *CBWS* algorithms have less number of working sensors than *GSS* and *GSB*.

Fig. 11 compares the detection probability of the four algorithms. The number of sensor nodes is ranging from 150 to 300. The comparison results by applying OPN, GN and RTN scenarios are shown in Figs. 11 (a), 11 (b) and 11 (c), respectively. The coverage quality indicates the required number of working sensors on each road. As shown in Fig. 11 (a), the proposed algorithms *WBWS* and *CBWS* achieve better performances than the existing algorithms *GSS* and *GSB*. This occurs because that the proposed *WBWS* and *CBWS* are prior to select the sensors with higher contributions to play the role of working sensors. However, the performance gap between the proposed algorithms and the existing algorithms is getting smaller when the number of required coverage is large. This occurs because that the four algorithms have similar situation that almost all sensors play the role of working sensor. Figs. 11 (b) and Fig. 11 (c) depict similar results as Fig. 11 (a). In general, the proposed *WBWS* and *CBWS* have better performance than existing algorithms *GSS* and *GSB* in all cases.

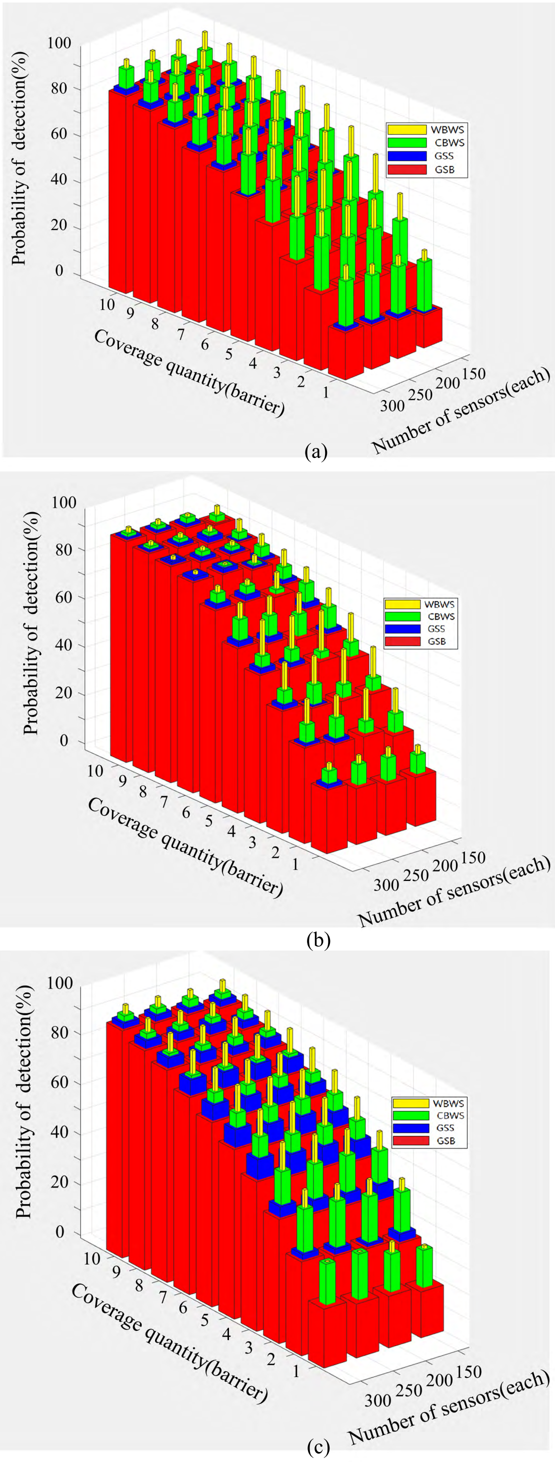


FIGURE 11. **(a) The comparisons of four algorithms in terms of the probability of detection in OPN scenario. (b) The comparisons of four algorithms in terms of the probability of detection in GN scenario. (c) The comparisons of four algorithms in terms of the probability of detection in RTN scenario.**

Fig. 12 compares the four algorithms in terms of the standard deviations of the contributions of the working sensors in each round. The contribution of each sensor is the supported monitoring quality of each working sensor. A low standard deviation of the set of working sensors indicates that all the working sensors contribute similar monitoring quality. Assume that there are n working sensors in a round. Let x_i be the contribution of working sensor s_i. The average contribution of the n working sensors is calculated as shown in Exp. (24).

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{24}$$

According to the value of Equ. (24). the standard deviation of the contribution of a working set can be calculated by applying Exp. (25).

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{25}$$

The average standard deviations are the summation of standard deviation value of each round divided by the number of rounds.

Fig. 12 compares the four algorithms in terms of the average standard deviations of contributions of the working sensors in each round. The vertical coordinate indicates the value of standard deviation, the horizontal coordinates indicate the number of barrier coverage. The comparison results by applying OPN, GN and RTN scenarios are shown in Figs. 12 (a), 12 (b) and 12 (c), respectively. As shown in Fig. 12 (a), the proposed algorithms *WBWS* and *CBWS* achieves smaller standard deviation than the existing algorithms *GSS* and *GSB*. This occurs because that the proposed *WBWS* and *CBWS* are prior to select the sensors with higher contributions to play the role of working sensors. Therefore, the contribution of each selected sensor is very similar. Figs. 11(b) and Fig. 11 (c) depict similar results as Fig. 11 (a). In general, the proposed *WBWS* and *CBWS* have better performance than existing algorithms *GSS* and *GSB* in all cases.

Fig. 13 investigates the lifetime of the WSNs by varying the number of sensors. The lifetime is measured by the number of rounds that the WSNs satisfies the monitoring quality. Fig. 13 (a) shows that the proposed *WBWS* and *CBWS* outperform the other mechanisms, in terms of lifetime. This occurs because that the algorithms *WBWS* and *CBWS* select a smaller number of sensors that can support the required monitoring quality. Moreover, the proposed *WBWS* and *CBWS* adopts PSM as their sensing model. Figs. 13 (b) and Fig. 13 (c) depict similar results as Fig. 13 (a). In general, the proposed *WBWS* and *CBWS* have longer lifetime than existing algorithms *GSS* and *GSB* in all cases.

The following table summarizes the comparisons of four algorithms in terms of properties including rich applied applications, number of working sensors, accuracy as well as lifetime. Compared with the related works *GSS* and *GSB*, the proposed two algorithms have better performances in terms of all considered properties. This occurs because that the existing *GSS* and *GSB* mainly apply Boolean Sensing Model which causes inaccurate detection, as compared with

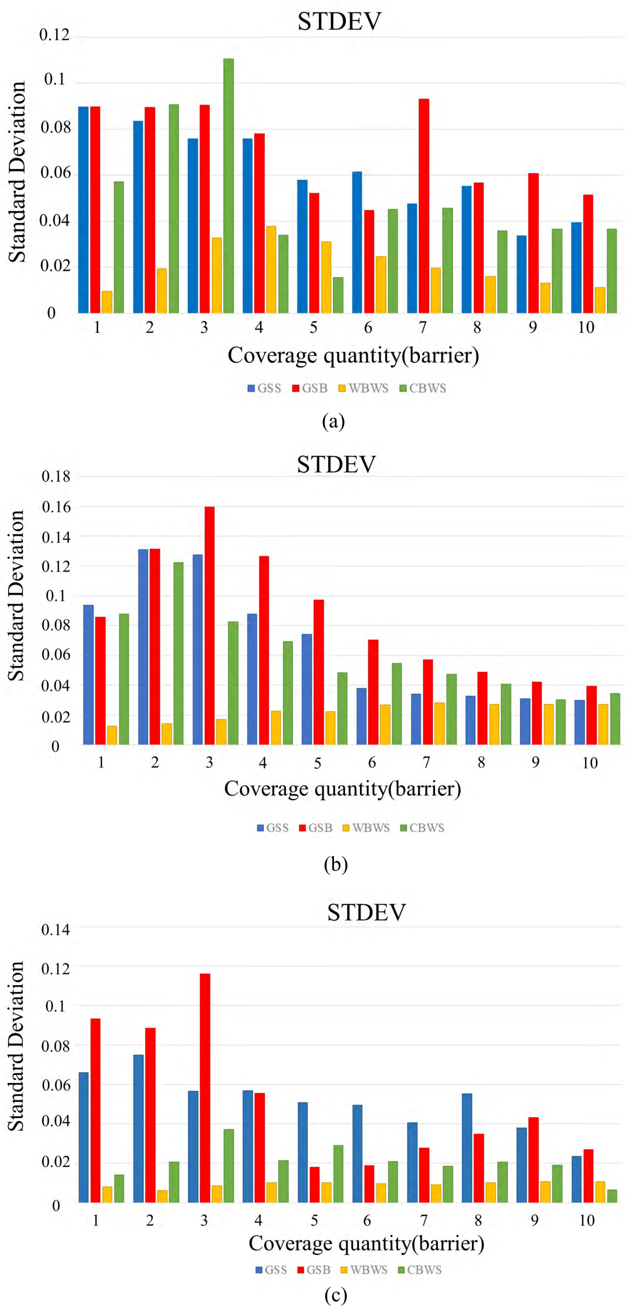


FIGURE 12. (a) The comparisons of four algorithms in terms of the Standard Deviation in OPN scenario. (b) The comparisons of four algorithms in terms of the Standard Deviation in GN scenario. (c) The comparisons of four algorithms in terms of the Standard Deviation in RTN scenario.

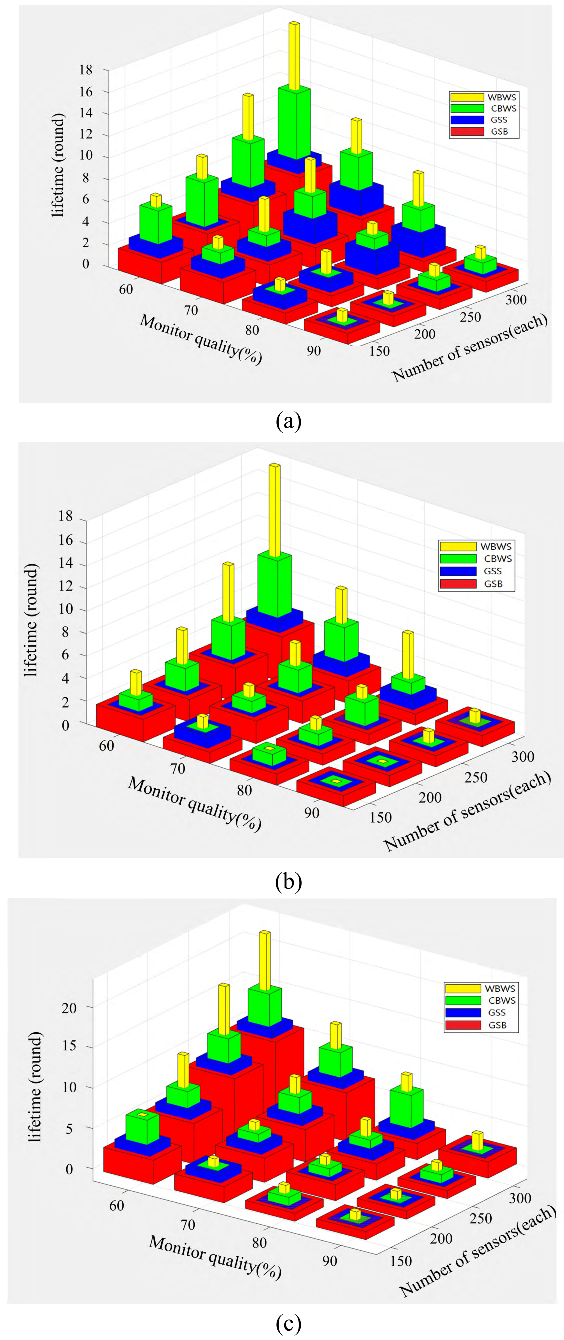


FIGURE 13. (a) The comparisons of four algorithms in terms of the lifetime in OPN scenario. (b) The comparisons of four algorithms in terms of the lifetime in GN scenario. (c) The comparisons of four algorithms in terms of the lifetime in RTN scenario.

the probabilistic sensing model which is applied by our algorithms. In addition, the existing *GSS* selects the sensor which can simultaneously monitor more than one road. Similar to *GSS*, the *GSB* selects the sensors belonging to the barrier which can simultaneously monitor more than one road. However, the policies applied in *GSS* and *GSB* might not select the sensor with largest contribution to the detection accuracy. Hence *GSS* and *GSB* require to wake up more sensors. On the contrary, the developed algorithms prior selects the sensor which has the largest contribution to the detection accuracy. As a result, the proposed algorithms outperform *GSS* and *GSB* in terms of the number of working sensors and the lifetime. In addition, the proposed *WBWS* outperforms the proposed *CBWS* in terms of accuracy. This occurs because that the proposed *WBWS* did not consider the connectivity issue and a large number of sensors can be selected to be the

TABLE 4. Comparisons of the proposed algorithms and the existing works in terms of several important features.

	Rich Applied Applications	Number of Working Sensors	Accuracy	Lifetime
WBWS	Many	Very Small	Very High	Long
CBWS	Many	Small	High	Medium
GSS	Medium	Large	Medium	Short
GSB	Medium	Very Large	Medium	Very Short

working sensor. However, the proposed *CBWS* which considers the connectivity issue can only select the working sensor from the neighbors of the current working sensors. Consequently, *WBWS* has a better performance than *CBWS*.

VI. CONCLUSIONS

The traffic flow counting is a new issue to be solved by applying the barrier coverage mechanism. This paper adopts the Probabilistic Sensing Model and investigates the barrier coverage issue which can be applied to solve the traffic flow counting problem. Two scheduling mechanisms, called *WBWS* and *CBWS*, are proposed, which aim to reach the predefined monitoring quality of traffics while satisfying the minimum numbers of working sensors. The two proposed mechanisms applying PSM as the sensing model which better matches the physical sensing behaviors of sensors. In addition, the proposed *WBWS* and *CBWS* carefully evaluate the contribution of each sensor and select the one that creates maximal cooperative contribution to be the working sensor. Compared with the recent studies, the proposed *WBWS* and *CBWS* significantly reduce the number of working sensors while the user-defined surveillance quality is satisfied.

REFERENCES

[1] M. Cardei, T. Thai, Y. Li, and W. Wu, "Energy-efficient target coverage in wireless sensor networks," in *Proc. IEEE INFOCOM*, Mar. 2005, pp. 1976–1984.

[2] C. F. Huang and Y. C. Tseng, "The coverage problem in a wireless sensor network," in *Proc. IEEE WSNA*, Sep. 2003, pp. 115–121.

[3] A. Gallais, J. Carle, D. Simplot-Ryl, and I. Stojmenovic, "Localized sensor area coverage with low communication overhead," in *Proc. IEEE PerCom*, Mar. 2006, pp. 327–337.

[4] Y. Zou and K. Chakrabarty, "A distributed coverage- and connectivity-centric technique for selecting active nodes in wireless sensor networks," *IEEE Trans. Comput.*, vol. 54, no. 8, pp. 978–991, Aug. 2005.

[5] M. Cardei and D.-Z. Du, "Improving wireless sensor network lifetime through power aware organization," *Wireless Netw.*, vol. 11, no. 3, pp. 333–340, 2005.

[6] S. Kumar, T. H. Lai, and A. Arora, "Barrier coverage with wireless sensors," in *Proc. ACM MobiCom*, Cologne, Germany, Aug. 2005, pp. 284–298.

[7] B. Liu, O. Dousse, and J. Wang, "Strong barrier coverage of wireless sensor networks," in *Proc. ACM MobiHoc*, Hong Kong, May 2008, pp. 411–420.

[8] P. Balister, B. Bollobas, A. Sarkar, and S. Kumar, "Reliable density estimates for coverage and connectivity in thin strips of finite length," in *Proc. ACM MobiCom*, Montreal, QC, Canada, Sep. 2007, pp. 75–86.

[9] A. Chen, T. H. Lai, and D. Xuan, "Measuring and guaranteeing quality of barrier coverage for general belts with wireless sensors," *ACM Trans. Sens. Netw.*, vol. 6, no. 1, Dec. 2009, Art. no. 2.

[10] A. Saipulla, C. Westphal, B. Liu, and J. Wang, "Barrier coverage with line-based deployed mobile sensors," *Ad Hoc Netw.*, vol. 11, no. 4, pp. 1381–1391, Jun. 2013.

[11] S. He, X. Gong, J. Zhang, J. Chen, and Y. Sun, "Curve-based deployment for barrier coverage in wireless sensor networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 2, pp. 724–735, Feb. 2014.

[12] A. Hossain, P. K. Biswas, and S. Chakrabarti, "Sensing models and its impact on network coverage in wireless sensor network," in *Proc. IEEE ICIIS*, Kharagpur, India, Dec. 2008, pp. 1–5.

[13] G. Yang and D. Qiao, "Barrier information coverage with wireless sensors," in *Proc. IEEE INFOCOM*, Janeiro, Brazil, Apr. 2009, pp. 918–926.

[14] J. K. Li, J. M. Chen, and T. H. Lai, "Energy-efficient intrusion detection with a barrier of probabilistic sensors: Global and local," *IEEE Trans. Wireless Commun.*, vol. 12, no. 9, pp. 4742–4775, Sep. 2013.

[15] S. Kumar *et al.*, "Maximizing the lifetime of a barrier of wireless sensors," *IEEE Trans. Mobile Comput.*, vol. 9, no. 8, pp. 1161–1172, Aug. 2010.

[16] A. Chen, S. Kumar, and T. H. Lai, "Designing localized algorithms for barrier coverage," in *Proc. ACM MobiCom*, Montreal, QC, Canada, Sep. 2007, pp. 63–74.

[17] C. Y. Chang, L.-L. Hung, Y.-C. Chen, and M.-H. Li, "On-supporting energy balanced k-barrier coverage in wireless sensor networks," in *Proc. ACM IWCMC*, Leipzig, Germany, Jun. 2009, pp. 274–278.

[18] C. Wang, B. Wang, H. Xu, and W. Liu, "Energy-efficient barrier coverage in WSNs with adjustable sensing ranges," in *Proc. IEEE VTC Spring*, Yokohama, Japan, May 2012, pp. 1–5.

[19] J. Du, C. Liu, H. Liu, and K. Sha, "Sleep-wakeup algorithms for virtual barriers of wireless sensor networks in 3D space," in *Proc. ACM MSN*, Hangzhou, China, Dec. 2010, pp. 47–52.

[20] H. Kim, J. Son, H. J. Chang, and H. Oh, "Event-driven partial barriers in wireless sensor networks," in *Proc. IEEE ICNC*, Kauai, HI, USA, Feb. 2016, pp. 1–5.

[21] H. Kim and J. Ben-Othman, "On resilient event-driven partial barriers in mobile sensor networks," in *Proc. IEEE ICC*, Kuala Lumpur, Malaysia, Jul. 2016, pp. 1–6.

[22] S. Kumar, T. H. Lai, M. E. Posner, and P. Sinha, "Optimal sleep-wakeup algorithms for barriers of wireless sensors," in *Proc. ACM MobiCom*, Sep. 2007, pp. 327–336.

[23] H. Mostafaei, M. U. Chowdhury, and M. S. Obaidat, "Border surveillance with WSN systems in a distributed manner," *IEEE Syst. J.*, 2018. doi: 10.1109/JSYST.2018.2794583.

[24] Z. Wang, H. Chen, Q. Cao, H. Qi, Z. Wang, and Q. Wang, "Achieving location error tolerant barrier coverage for wireless sensor networks," *ELSEVIER Comput. Netw.*, vol. 112, pp. 314–328, Jan. 2017.

[25] H. Mostafaei, M. Shojafar, B. Zaher, and M. Singhal, "Barrier coverage of WSNs with the imperialist competitive algorithm," *J. Supercomput.*, vol. 73, no. 11, pp. 4957–4980, Nov. 2017.

[26] H. Mostafaei and M. R. Meybodi, "An energy efficient barrier coverage algorithm for wireless sensor networks," *Wireless Pers. Commun.*, vol. 77, no. 3, pp. 2099–2115, Aug. 2014.

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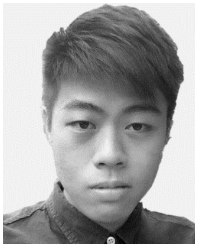

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