On Barrier Coverage in Wireless Camera Sensor Networks

Kuei-Ping Shih, Chien-Min Chou, I-Hsin Liu, and Chun-Chih Li

Department of Computer Science and Information Engineering
Tamkang University, Tamshui 251, Taipei, Taiwan
kpshih@mail.tku.edu.tw

Abstract—The paper proposed a distributed algorithm, namely CoBRA (Cone-based Barrier coveRage Algorithm), to achieve barrier coverage in wireless camera sensor networks (WCSNs). To the best understanding, CoBRA is the first algorithm which try to deal with the barrier coverage issue in WCSNs. Based on some obserbations, the basic concept of CoBRA is that each camera sensor can determine the local possible barrier lines according to the geographical relations with their neighbors. A sink in a WCSN initiates Barrier Request (BREQ) messages to form the possible barrier lines. Afterward, a barrier line is constructed by the Barrier Reply (BREQ) message initiated by another sink. CoBRA mainly includes three phases: Initial Phase, Candidate Selection Phase, and Decision Phase. In the Initial Phase, each camera sensor collects the local information of its neighbors and estimates the possible barrier lines. In the Candidate Selection Phase, a sink initiates the BREQ packets and forwards the BREQ packets to camera sensors. Camera sensors receiving the BREQ then reforward the BREQ packets to its neighbors who are capable of forming a barrier line. All camera sensors receiving the BREQ will forward the BREQ to their neighbors again in the same manner. Finally, in the decision phase, after the BREQ message is transmitted through the whole monitoring area, a BREP message is used by the sink to select a barrier line in a WCSN. The barrier coverage is achieved by finding the barrier line in the monitoring area. Experiment results show that CoBRA can efficiently achieve barrier coverage in WCSNs. Comparing to the ideal results, CoBRA can use fewer nodes to accomplish barrier coverage in random deployment scenarios.

I. INTRODUCTION

With the rapid development and advancement in Micro-Electro-Mechanical systems (MEMS) [1] and wireless communication technologies, small size, low-cost, multi-functional sensors with wireless communication capabilities can be implemented nowadays. Sensors are capable of sensing, computing, and communicating with other sensors. Basically, each sensor can be equipped with a number of sensing units. The sensing units can be changed to meet the practical applications. For example, the MICA2[2] can sense temperature, humidity, pressure and other properties according to the requirements and scenarios.

Camera sensors which are sensors equipped with cameras can be used for sensing visual data, such as images or motion pictures.[3], [4], [5]. Besides, camera sensors are also considered to achieve target coverage[6] or to localize objects[7]. The visual data captured by camera sensors can be used for identifying the sensing objects. As a result, many applications are suitable of using camera sensors to take the responsibility of sensing tasks. Many areas, such as ecological protection areas, exhibition areas, prisons and other places, are also suitable of using camera sensors. Many camera sensors can form a Wireless Camera Sensor Network (WCSN).

Barrier coverage is a widely discussed topic in wireless sensor networks. In wireless sensor networks, the barrier coverage problem in the monitoring area is defined as follows: when an object is moving from a particular direction to an opposite direction and crossing the area deployed with sensors. The moving object must be detected by at least one sensor deployed in the area. Previous researches [3], [8], [9] only addressed the barrier coverage with uni-directional sensing ability sensors. However, with the help of camera sensors, barrier coverage can be applied into different fields. The combination of cameras and sensors bring several applications and research issues.

However, the sensing field of a camera sensor is different from that of a conventional sensor. The sensing field of a sensor in WSNs is circular. Current algorithms which try to solve the coverage issues are based on the circular sensing area of a sensor [8], [10], [11], [12]. However, the different sensing field of a sensor in WCSNs and in WSNs is likely to cause some sensing holes when using a WCSN to form barrier coverage in the sensing area[13].

Taking Fig. 1(a) for example, if an intruder is trying to cross the monitoring area, the intruder will be sensed by a sensor with uni-directional sensing ability in a WSN. However, if the same barrier coverage mechanism or algorithm is applied in a WCSN, the WCSN may not be able to achieve barrier coverage to sense the intruder. Fig. 1(b) shows the condition of applying a traditional barrier coverage algorithm on a WCSN. There still exists several sensing holes in the sensing area. As a result, a new barrier coverage algorithm is needed for WCSNs.

In the paper, a distributed algorithm, Cone-based Barrier coveRage Algorithm (CoBRA) to solve the barrier coverage issue in WCSNs is proposed. To the best understanding, CoBRA is the first algorithm addressed with the barrier coverage problem in WCSNs. CoBRA includes three phases: the *Initial Phase*, the *Candidate Selection Phase*, and the *Decision Phase*.
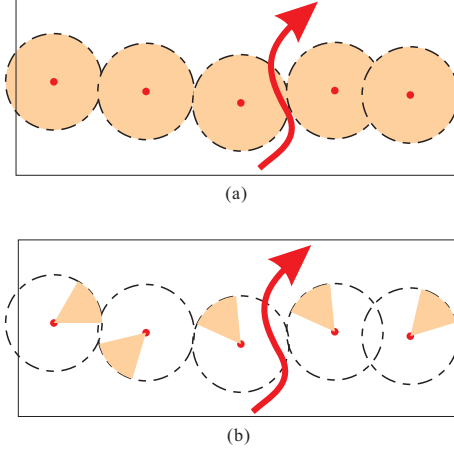
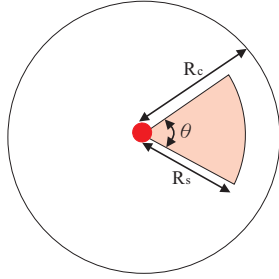Fig. 1. Traditional barrier coverage problem in WSNs is not suitable in WCNS.

Fig. 2. The sensing model of a camera sensor.

In the Initial Phase, each camera sensor collects the neighbor information and determines the possible barrier lines for further usage. In the Candidate Selection Phase, two different types of packets, the Barrier Request (BREQ) packet is used for finding a barrier line in WCSNs. In the Decision Phase, the Barrier Reply (BREP) packet is used for forming the barrier line in WCSNs. Each camera sensor determines if it needs to wake up or not. Besides, the awaking sensors also need to determine their sensing directions by the information gathered from neighbors. As a result, camera sensors in CoBRA can form barrier lines in a distributed manner.

The rest of the paper is organized as follows. Section II describes the assumptions, notations, definitions, and network model. In Section III, the proposed protocol, CoBRA is described. Besides, the paper also proposed a divide-and-conquer algorithm in Section III in order to compare with CoBRA. Section IV is the simulation results of CoBRA. Section V concludes the paper.

II. PRELIMINARY

The section specifies the definitions, notations, and terminologies of the paper. Besides, the network model used in the paper is also addressed.

A. Notations and Definitions
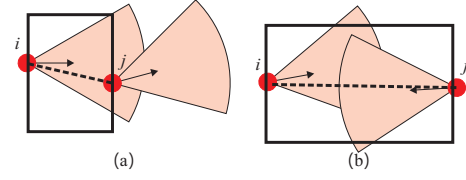
Definition 1: Intruder path

Fig. 3. (a) Sensor i covers sensor j with its sensing area and forms a sensing connect between sensor i and j. (b) Sensor i and j cannot cover each other. But the sensing area of sensor i and j are interconnect. Sensor i and j are sensing connected.

When an intruder tries to cross the monitoring area, the intruder will cross two boundaries of the monitoring area one after another. The first crossing point at the boundary can be viewed as the start point of the intruder. On the other hand, the second crossing point at the boundary can be viewed as the exit point of the intruder. The link of the two crossing points can also be regarded as the intruder direction.

Definition 2: Sensing range R_s and communication range R_c

The farthest distance that a camera sensor can identify the intruder is defined as the sensing range R_s of a camera sensor. The farthest distance that a camera sensor can communicate with other camera sensors is defined as the communication range R_c. In the paper, R_c is twice as R_s.

Definition 3: Field of view θ

The biggest angle a camera sensor can sense is defined as the field of view. The sensing interface of a camera sensor is the camera. Therefore, field of view θ is the angle that the sensing interface can be used for sensing.

Definition 4: Sensing area

The area that a camera sensor can monitor at a time is defined as the sensing area. To sum up, the sensing area is determined by the sensing range and the field of view of a camera sensor.

Definition 5: Sensing connected sensors

If the sensing areas of two camera sensors overlap with each other or the sensing area of a camera sensor covers another camera sensor, the two camera sensors are *sensing connected*. Fig. 3 shows the examples of sensing connected sensors. In Fig. 3(a), sensor i covers sensor j, consequently, sensor i and j are sensing connected. In Fig. 3(b), the sensing areas of sensor i and j overlap with each other. Therefore, sensor i and j are sensing connected.

Definition 6: Barrier line

If two camera sensors are sensing connect, then there exists a barrier line between the two camera sensors. An intruder who tries to across the barrier line will be sensed by at least one camera sensor. Taking Fig. 3 as an example, sensor i and j are sensing connected. Therefore, the dashed line between sensor i and j is the barrier line. If the monitoring area is the black rectangle and the intruder wants to cross the monitoring area from the bottom to the top of the rectangle, the intruder's path will intersect with the barrier line at least at one point. It means that the intruder will be sensed by at least one camera sensor when crossing the monitoring area.
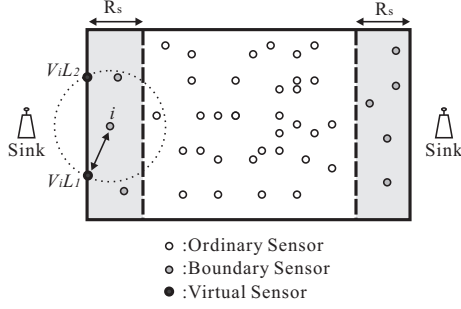
Fig. 4.   The network model of CoBRA.

Definition 7: Boundary sensors, ordinary sensors, and virtual sensors

Camera sensors whose physical distances to one of the two vertical boundaries are shorter than R_s are boundary sensors. Fig. 4. shows the network model of CoBRA. In Fig. 4, each circle is a camera sensor. The distances of the circles with of gray center to one of the vertical boundaries are shorter than R_s. Therefore, the circle with gray center in Fig. 4 are boundary sensors. All the deployed cameras except the boundary sensors are ordinary sensors. In Fig. 4, the circle with white center in Fig. 4 are ordinary sensors.

Virtual sensors are not physical sensors. Virtual sensors are logical sensors located on the vertical boundaries. In order to form a barrier line in the monitoring area, camera sensors have to cover the vertical boundaries. Consequently, virtual sensors are logical sensors and should be covering by boundary sensors. In Fig. 4, there exists two virtual sensors V_iL_1 and V_iL_2 for boundary sensor i. If camera sensor i is used for constructing a barrier line, sensor i has to cover one of its virtual sensors in order to form a barrier line between itself and the vertical boundary.

B. Assumption and Network Model

In the paper, the monitoring area is assumed to be a rectangle. The height and weight of the monitoring area is W x H. All camera sensors are randomly deployed in the monitoring area. The sensing area of a camera sensor is a sector. The view angle of a camera sensor is θ. Fig. 2 shows the sensing model of a camera sensor. All camera sensors are homogeneous. In other words, all camera sensors have the same sensing range R_s, the same field of view θ, and the same communication range R_c. Two sinks are located at the boundary of the monitoring area. Besides, the sinks can directly communicate with the boundary sensors. All sensors are capable of knowing their location information by GPS or a certain localization algorithm[14], [15].

III.   Cone-base Barrier coveRage Algorithm (CoBRA)

In this section, some observations under WCSNs are addressed. The proposed algorithm, CoBRA, is also addressed in this section by exploiting the observations in WCSNs. Finally,
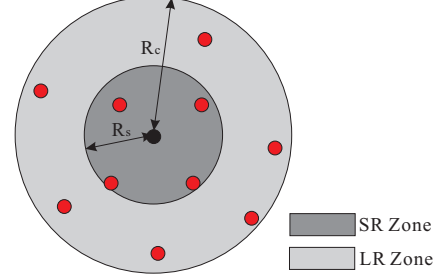

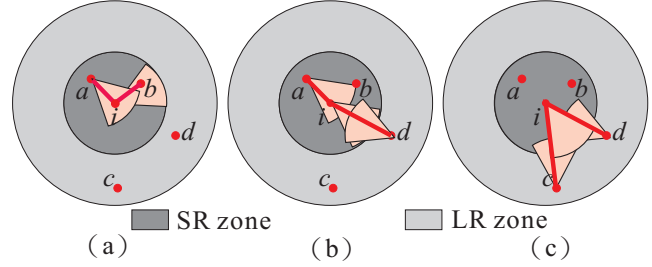Fig. 5.   The definition of SR zone and LR zone.

Fig. 6.   Three different types of barrier lines. (a)Type SS. (b)Type SL. (c)Type LL.

a heuristic approach, Divide-and-Conquer, for comparison with CoBRA are also addressed in this section.

A. Observations of WCSNs

Since the communication range is twice as the sensing range, the neighbors of a camera sensor can be divided into two groups according to their distances to the camera sensor. Fig. 5 shows the two zones of a camera sensor. All the neighbors of a camera sensor must be located in the SR (Shorter than transmission Range) zone or LR (Longer than transmission zone) zone.

Initially, all camera sensors collect the information of their neighbors through message exchanges. Each camera sensor then can estimate the possible barrier lines for further usage according to the geographical relations of its neighbors and itself. According to the geographical relations among sensors, a camera sensor can form three different kinds of barrier lines with its neighbors. Fig. 6(a) shows the type SS barrier line. Camera sensor a and b are neighbors of camera sensor i and both of them are located within the SR zone of camera sensor i. As a result, camera sensor a, b, and i can form a barrier line of type SS. From the aspect of sensor i, it means a and i are sensing connected, since camera a covers camera sensor i. Besides, camera sensor i and b are also sensing connected, since b is covered by camera sensor i. To sum up, a barrier line can be formed from camera sensor a to i to b. Since the barrier line is formed by camera sensor i and two of its neighbors within the SR zone, the barrier line is called type SS.

In the same manner, the barrier line that a sensor can construct with its neighbors can be composed by two types of
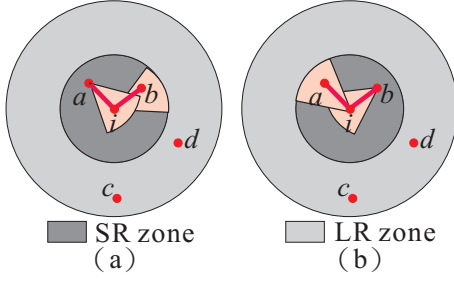
Fig. 7. Barrier line of type SS can be formed by using different camera sensors. (a)Barrier line formed by a and i. (b)Barrier line formed by i and b.

Fig. 8. An example of camera sensor and its neighbors.(a) Camera sensor i with 4 neighbors. (b) The stored information of camera sensor i.

neighbors, sensors within the SR zone and LR zone. Therefore, totally three types of barrier lines can be formed in WCSNs, barrier line of type SS, type SL, and type LL. The type SS barrier line is a sensor selects two neighbors to build a barrier line where both of them are within the SR zone. Fig. 6(a) shows the barrier line of type SS. The type SL is that a sensor selects two of its neighbors to build a barrier line. One of its neighbor is located within the SR zone and the other is located in the LR zone. Fig. 6(b) shows the barrier line of type SL. Finally, Fig. 6(c) shows the barrier line of type LL. The barrier line in Fig. 6(c) is composed by camera sensor i and two camera sensors located within the LR zone of i.

Different types of barrier lines need to use different number of camera sensors. Barrier line of Type SS only needs two out of three camera sensors to form the barrier line. In Fig. 7(a), only camera sensor a and i should be active to form a barrier line. Additionally, the working of camera sensor i and b can also form a barrier line of type SS in Fig. 7(b). As a result, the unused camera sensor can be used to sustain another barrier line or to turn off its camera in order to save energy.

However, in barrier lines of type SL and LL, all three sensors are needed to turn on their cameras to form a barrier line. Fig. 6(b) shows that sensor a, b, and i should wake up and use their camera to form a barrier line of type SL. The condition in barrier line of type LL is more critical than other two types. In Fig. 6(c), sensor c and d are located in the LR zone of sensor i. Besides, the coverage area of sensor i needs to connect with the coverage areas of sensor c and d. As a result, the angle of $\angle cid$ has to be smaller or equal to the field of view θ.

B. The proposed algorithm

In order to achieve barrier coverage in the monitoring area, the paper proposes a distributed algorithm, CoBRA, to achieve barrier coverage in WCSNs. CoBRA mainly includes three phases, the **Initial Phase**, the **Candidate Selection Phase**, and the **Decision Phase**. The description of the three phases are described as follows.

1) Initial Phase: In the initial phase, each camera sensor needs to collect its neighbor information through message exchanges. Each camera sensor will broadcast its locaton to its neighbors. Camera sensors who receive the information broadcasted from its neighbors will also record the locations
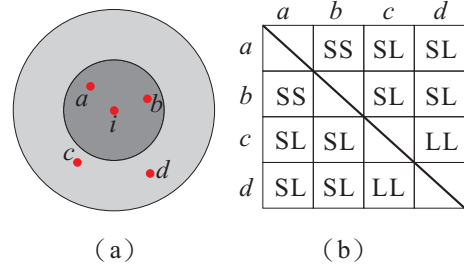
of its neighbors. Therefore, each camera sensor will maintain a neighbor list and know the distances between itself to its neighbors. Besides, camera sensors can also estimate the possible barrier lines with its neighbors and store the estimated information in its memory. Fig. 8 shows an example of the information collected and stored in a camera sensor. In Fig. 8(a), camera sensor i has 4 neighbors, a, b, c, and d. Therefore, camera sensor i can form different barrier lines with its neighbors. The table in Fig. 8(b) shows the stored information of camera sensor i. Camera sensor a and b are both located within the SR zone of camera sensor i. Therefore, by looking up the stored table, it can be observed that camera sensor i can form a barrier line of type SS with camera sensor a and b. Each camera sensor collects their neighbor information and the stored information will be used in the candidate selection phase.

2) Candidate Selection Phase: In the candidate selection phase, a sink sends the BREQ message to boundary sensors firstly. In order to maintain the sensing connection with the boundary, boundary sensors assume there are virtual sensors located at the boundary. Because virtual sensors are only concepts in the network model, the boundary sensors have to cover the virtual sensors in order to maintain the sensing connnection with the virtual sensor and to form a barrier line. Besides, virtual sensors will also be the start points of barrier lines. Afterward, a boundary sensor selects neighbors from its neighbor list to form possible barrier lines. Therefore, the boundary sensors who receive the BREQ from the sink will forward the BREQ to their neighbors who are capable of forming barrier lines.

In Fig. 9(a), sensor b is a boundary sensor and the dash line is the boundary of the monitoring area. In order to maintain the sensing connection, a virtual sensor $V_b L_i$ is adopted for sensor b. According to the above explanation, camera sensor b has to cover the virtual sensor $V_b L_i$. In other words, sensor b's camera has been used up. Consequently, in order to extend the barrier line to another sensor, sensor b has to find one of its neighboring sensors who are capable of covering sensor b. Therefore, one of camera sensor b's neighbor, c, needs to cover sensor b to extend the barrier line began from virtual sensor $V_b L_i$. Therefore, sensor b will forward the BREQ to its neighbors to find potential candidates who can extend the barrier line. A parameter, *HelpBit*, in the BREQ is used to

BREQ$_i$	
Source Sensor ID	Source Sensor Location
Sender ID	Sender Location
CandidateID$_1$	Helpbit$_1$
CandidateID$_2$	Helpbit$_2$
$\cdots$	$\cdots$

TABLE I
THE FORMAT OF BREQ

BREP$_i$
Source Sensor ID
Last Hop Sensor ID

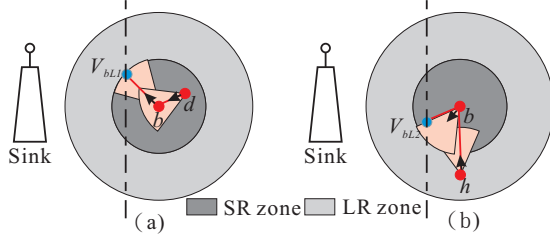TABLE II
THE FORMAT OF BREP.

Fig. 9. Boundary sensors forms a barrier line with virtual sensors (a)Type SS. (b)Type SL.

indicate that the camera of a sensor is needed to support the sender of BREQ or not. If the HelpBit is set to 1, it means that the receiver's camera needs to maintain the sensing connect with the forwarder of BREQ. Otherwise, the usage of the camera can be determined by the receiver of BREQ. Take Fig. 9(a) as an example, sensor b has to cover virtual sensor V_bL_i. Therefore, when sensor b forward the BREQ to sensor c, the HelpBit in the BREQ to sensor c will be set to 1. Consequently, sensor c knows that it has to cover sensor b in order to form a barrier line. In Fig. 9(b), the virtual sensor V_bL_i, boundary sensor b, and ordinary sensor h only can from a type SL barrier line. Therefore, camera sensor b has to cover the virtual sensor V_bL_i and a part of the link between camera sensor b and h. The barrier line in Fig. 9(b) can also be extended.

Table I shows the format of BREQ. The initiator of BREQ will be recorded in the header of BREQ. Besides, the sender of the BREQ will also be recorded. When a camera sensor receives a BREQ, the sensor will check the HelpBit and the local information to determine if it can extend the barrier line with the sender of the BREQ. If the answer is "no", the sensor will discard the BREQ message. The barrier line cannot be extended through the sensor. On the contrary, if the answer is "yes", the sender will also try to find out if there exists some neighboring sensors who are capable of extending the barrier line. Then the sensor will add these possible candidates in the BREQ and forward the BREQ to these candidates. Sensors who receive the BREQ will find out the possible candidates from its neighbors. Then the sensor will re-forward the BREQ to those possible candidates to extend the barrier line.

As a result, when a ordinary sensor receives the BREQ from other camera sensors, the ordinary sensor will do the above decision polcy and choose to re-forward or to discard the BREQ message. Until the BREQ message is sent through the whole WCSN to the second sink. The sink can determine if

a barrier line exists or not and replies the BREP message to form a barrier line officially.

3) Decision Step: When a sink transmits the BREQ message through the whole WCSN to another sink, the sink is likely to receive multiple copy of BREQs. Multiple BREQs mean different barrier lines. It is possible for the sink to select a barrier with minimum number of camera sensors. Therefore, the sink is likely to wait for a time period before replying a BREP message after receiving the first BREQ. After the time period is end, the sink chooses a barrier line with the minimum hop count and replies the BREP to the previous camera sensor. Table II shows the format of BREP messages. Each camera sensor records the sender and the receiver of each received and transitted BREQ messages. As a result, when a sensor receives a BREP message, the sensor can forward the BREP message to the dedicated neighbor to contruct the barrier line. Besides, each sensor will rotate is camera to the designated direction to fullfil the requirement of sensing connection with its neighbors. When the BREQ message is transmitted from one sink to another through the whole WCSN, the barrier line is constructed by camera sensors.

C. Divide-and-conquer

In a WCSN, there may exist a large number of camera sensors. Therefore, to find a barrier line in a centralized manner is likely to have high complexity. A heuristic centralized approach, Divide-and-conquer is also addressed in the paper. The concept of Divide-and-conquer approach is described as follow.

In the Divide-and-conquer approach, the monitoring area will be divided into two sub-areas in order to lower the computing complexity firstly. However, the two sub-areas may still have large number of camera sensors. As a result, the monitoring area will be divided into smaller area recursively. After the whole monitoring area are divided into the smallest areas. It is likely to find barrier lines in these areas efficiently.

After dividing the monitoring area into the smallest areas and finding barrier lines in these area. The areas with its barrier line need to be combine to a large area. And the barrier lines in these areas also need to be connected into a longer barrier line. Recursively repeating the "conquer" process. As a result, a barrier line can be found in the monitoring area.

IV. PERFORMANCE EVALUATION

In this section, CoBRA is evaluated via the C++ language. The detailed parameters are listed in Table III.

Fig. 10 shows the relationship between the number of camera sensors and the successful rate of finding a barrier line. The evalation result shows that if there are more and

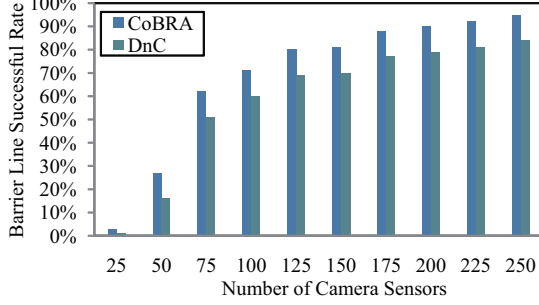| Simulation parameters	
Monitor Area(W x H)	500-1500*500 m^2
Camera Sensors	50-750
Communication Range	100 m
Sensing Range	50 m
Field of View	$\pi/6$-$\pi/2$

TABLE III
SIMULATION PARAMETERS

Fig. 11. Successful probability of finding a barrier line under different width of monitoring area.

Fig. 10. Successful probability of finding a barrier line under different number of camera sensors.

Fig. 12. Successful probability of finding a barrier line under different field of view.

more camera sensors in the monitoring area, the probability of finding a barrier line is higher. In comparison with the centralized heuristic Divide-and-conquer (DnC) approaches, CoBRA has higher probability of finding a barrier line with the same number of camera sensors.

The density of camera sensors in the monitoring area also influences the probability of finding a barrier line in WCSNs. Fig. 11 shows the successful probability of finding a barrier line by using CoBRA and Divide-and-conquer approach. The percentage in the legend in Fig. 11 means the density of camera sensors in the monitoring area. 0.1% means there exists a camera sensor in 1000 m^2 (1/1000). The result shows that the successful rate of using CoBRA is stable when the density of camera sensors is higher than 0.05% in the monitoring area. The probability of finding a barrier line in the Divide-and-conquer approach suffers from the low density of camera sensors. However, CoBRA still has good performance under low density.

The field of view also has great impact on finding a barrier line in WCSNs. Fig. 12 shows the successful probability of finding a barrier line under differnt field of view. The results in Fig. 12 show that if the density is higher than 0.04%, FOV has little effect on finding a barrier line. However, if the density of camera sensors in the monitoring area is lower than 0.02%, FOV has great effect on the successful probability of finding a barrier line. Therefore, increasing the FOV of camera sensors will also increase the successful probability of finding a barrier line.

Fig. 13 shows the comparision among CoBRA, ideal approach, and the Divide-and-conquer approach. The ideal approach indicates the minimum number of camera sensors needed to find a barrier line. The simulation results in Fig. 13 show that the CoBRA can find a barrier line with small number
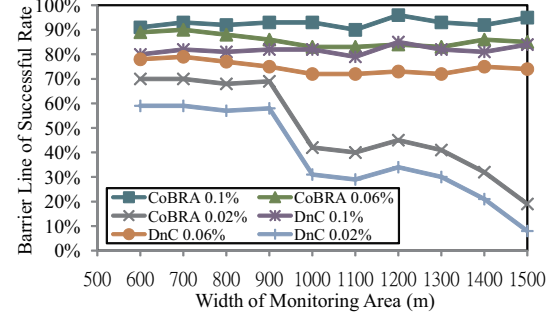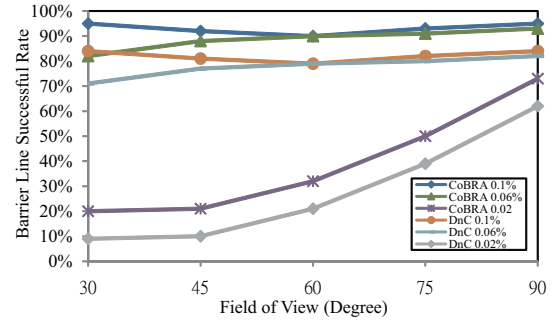
of camera sensors. The Divide-and-conquer approach falls behind the ideal approach and CoBRA.

V. CONCLUSIONS

The paper proposes a distributed protocol, CoBRA, to find barrier lines in WCSNs. CoBRA is designed according to the observations in WCSNs. To the best understanding, CoBRA is the first algorithm tries to deal with the barrier coverage problem in WCSNs. In CoBRA, a sensor can build the possible barrier line relationship according to the distance between itself and its neighbors. Afterward, sensors can select the candidates of the barrier line through the transmission of BREQ messages. Possible barrier lines will be constructed through the transmission of BREQ and BREP messages. A barrier line can be build with the minimum number of camera sensors. Sensors who receives the BREP messages will be able to determine the awake/sleep status of their cameras and rotate their cameras to the designated direction. The simulation results show that CoBRA can find a barrier line with few sensors. In the future, CoBRA will be extend to an algorithm which can be used to find multiple barrier lines and to schedule the barrier lines in order to detect the intruder while saving more energy to extend the lifetime of camera sensors. Besides, CoBRA also can be applied into 3D space in the future.
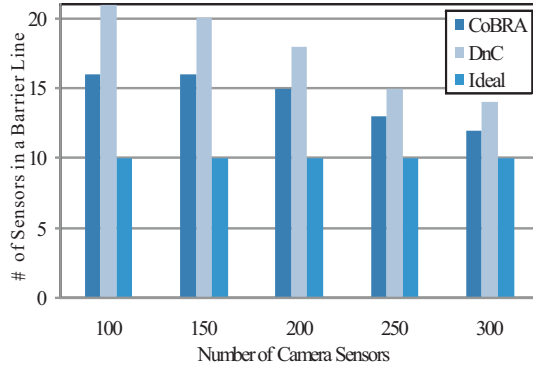
Fig. 13. Number of barrier lines can be found under different approaches.

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