Constructing Belt-barrier Providing β-Quality of Monitoring with Minimum Camera Sensors

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***Abstract*—A wireless sensor network is said to form a belt-barrier for a region if it is able to detect any object moving from outside the region to inside. Recently, Cheng and Tsai found if camera sensors are used to form a belt-barrier, the breadth of the barrier becomes an important quality factor to ensure high quality of monitoring (QoM). Then, they proposed the minimum β-breadth belt-barrier construction problem ((β, 1)-B^{3}CP) whose goal is to select a minimum number of camera sensors to form a β-breadth belt-barrier, which ensures the width of the picture of any object which moves through the barrier is at least β. In this paper, we perform more thorough investigation of the problem and introduce a *new polynomial time exact algorithm* for the problem under the assumption that the angle of each camera is fixed. Our simulation result shows our algorithm outperforms Cheng and Tsai's algorithm. We also introduce a variation of (β, 1)-B^{3}CP, namely (β, k)-B^{3}CP, which aims to construct k node-disjoint β-breadth belt-barrier for fault-tolerance purpose, propose a new heuristic algorithm for it, and conduct simulations to evaluate its performance.**

***Index Terms*—Wireless sensor network, camera sensor network, exact algorithm, graph theory, quality of monitoring.**

I. Introduction

Over the past years, wireless sensor network, a wireless network of microelectronic computing devices equipped with one or more sensors and a wireless signal transceiver, has received a significant amount of attentions from academia, industry, and military for a broad range of applications. A wireless sensor network forms a belt-barrier around an area of interest if it can detect any object moving from outside the area to inside [11]. Frequently, the surveillance capability of the belt-barrier is refereed as barrier-coverage. Barrier-coverage is known to be a mandatory quality of wireless sensor network in several important applications such as intrusion detection and border surveillance.

Depending on the shape of the sensing area, a sensor node is classified as either an omni-directional sensor node, whose sensing area resembles a circle centered at the node [2], or a directional sensor node with a sector-like sensing area. As the sensor network related technology advances and sensor networks can manage more amount of information, camera sensor network, which consists of wireless sensor nodes with visual sensors and thus is a special kind of directional sensor network, is getting more attentions [3], [4], [5], [6], [9], [10].

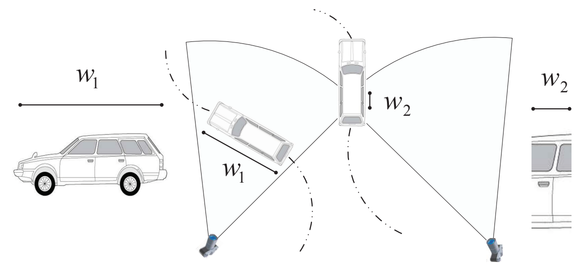

Fig. 1. Illustration of breadth

Compared to the traditional scalar sensors used to measure temperatures, humidity, etc., the quality of the information that a camera sensor can provide from an observed object is related to the trajectory of the object. For instance, consider the belt-barrier of camera sensors in Fig. 1. This example shows when an object is crossing the barrier of the camera sensors, depending on its trajectory, the width of the picture of the object taken by the camera barrier can be significantly different, e.g. w_1 and w_2 in the figure. Depending on the application, a picture with very small width may not be meaningful.

In [10], the authors pointed out the breadth of a belt-barrier of camera sensors is significant to ensure high quality of monitoring (QoM). Based on this observation, they proposed a new camera sensor subset selection problem from a given camera sensor network such that the subset forms a camera barrier, which monitors any intruder moving from one side of a squared region (an area of interest) to the opposite side, with minimum breadth of β, i.e. the width of the picture of the intruder taken by the barrier is guaranteed to be at least β. They defined a camera belt-barrier satisfying the requirement as a β-breadth belt-barrier, and the QoM provided by such belt-barrier as β-QoM. During the rest of this paper, we will refer this problem as the minimum β-breadth belt-barrier construction problem ((β, 1)-B^{3}CP). The contributions of this paper are as follows.

(a) In [10], the authors proposed two algorithms for (β, 1)-B^{3}CP, namely the basic distributed β-breadth belt-barrier construction algorithm (D-TriB) and the enhanced distributed β-breadth belt-barrier construction algorithm with rotation (D-TriBR). The main difference D-TriB and D-TriBR is that while D-TriB assumes the direction of each camera is fixed, D-TriBR assumes it can be freely rotated. In this paper, we assume the direction of each camera is fixed and introduce a *polynomial time optimal algorithm* for (β, 1)-B^{3}CP, namely (β, 1)-B^3 computation algorithm ((β, 1)-B^{3}CA). Our simulation result shows our (β, 1)-B^{3}CA outperforms D-TriB [10].

(b) Frequently, wireless camera sensor networks are deployed over very hostile and hazardous environments and thus sensor nodes are likely to be faulty. Due to the reason, it is desirable to operate more than one β-breadth belt-barrier at the same time to improve the fault-tolerance. Motivated by this observation, we introduce the k concurrent β-breadth belt-barrier construction problem ((β, k)-B^{3}CP), whose goal is to compute k node-disjoint β-breadth belt-barriers from a given set of camera sensor nodes with fixed camera direction. We introduce a new heuristic algorithm for (β, k)-B^{3}CP, namely (β, k)-B^{3}CA and evaluate the average performance of the algorithm via simulation.

The rest of this paper is organized as follows. Section II presents related work. Some preliminaries and the definitions of the problems of our interest are given in Section III. Section IV and Section V present our main results, which include (β, 1)-B^{3}CA and (β, k)-B^{3}CA. We present our simulation result and corresponding analysis in Section VI. Finally, we conclude this paper in Section VII.

II. Related Work

The concept of barrier-coverage is first introduced by Gage in the context of robotic sensor [18]. In [1], Saipulla et al. investigated how to provide barrier-coverage using a group of sensors with limited mobility. The concepts of strong and weak camera barrier have been introduced by Zhang et al. [20]. In [17], Chen et al. proposed an effective way to measure the quality of barrier coverage for a belt region, and the bound of the region width can be used to measure the quality of the barrier. In [12], Kumar et al. has proposed a centralized k-barrier construction algorithm. They also provided the relationship between the success rate of barrier construction and the number of sensors required to find the optimal number of sensors to scatter in a randomly deployed scenario.

Recently, a considerable amount of effort was made on wireless camera sensor networks and their applications [4], [5], [6], [9], [2]. Camera sensor networks have several unique requirements, and therefore many existing algorithms for traditional wireless sensor networks are not applicable to camera sensor networks directly [7], [8]. In [6], Shih et al. has made the first effort to investigate a barrier-coverage problem in wireless camera sensor networks, and proposed a distributed protocol called CoBRA. Fusco et al. [19] studied the k coverage problem in directional sensor networks and proposed an algorithm which is called greedy algorithm (GA). GA is a distributed algorithm and selects k directional sensors whose viewing angle can be rotated to solve the coverage problem. However, the number of cameras selected by GA is not optimal. For coverage detection in wireless camera sensor networks, Johnson et al. [5] proposed an optimal dynamic programming algorithm for a geometrically constrained setting for the pan and scan problem, in which cameras are configured to observe multiple target locations.

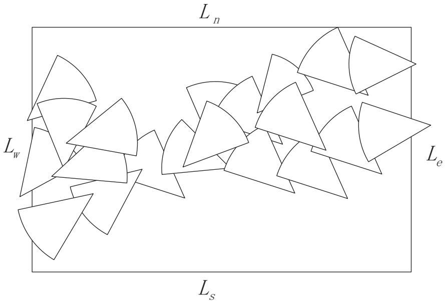

Fig. 2. Given a rectangular belt region R, L_w, L_n, L_e, and L_s represent the left, top, right, bottom borders of R, respectively.

In [10], Cheng et al. introduced the concept of the breadth in the barrier coverage in camera sensor networks. A distributed β-breadth belt-barrier algorithm is proposed to construct an effective barrier which ensures that an image of at least β-breadth will be captured wherever an intruder gets in. In this paper, we aim to introduce a better algorithm for a problem considered by Cheng et al. as well as investigate a fault-tolerant version of the problem.

III. Preliminaries and Problem Definitions

In this paper, we assume that a set S of n camera sensors, $\{s_1, s_2, \cdots, s_n\}$, are randomly deployed over a rectangular belt region R and we would like to detect any intruder moving from the upper border line of R to the bottom border line of R, i.e. L_n and L_s in Fig. 2, respectively. We further assume the location of each camera sensor is known in advance by using an embedded GPS or a localization algorithm. For each sensor node, we assume there exists only one embedded camera sensor whose viewing angle is not adjustable. Note that we also use s_i to denote the sensing sector (the area covered by s_i) of s_i interchangeably. It is popular to assume that for each s_i, the sensing range of s_i is r and the communication range of s_i is at least $2r$ [24]. In this paper, for simplicity, we assume the communication range of the sensor of our interest is exactly $2r$. The field-of-view (FOV) of s_i is denoted by $\theta_i (0 \leq \theta \leq \pi/2)$. In addition to θ_i, we define θ_{1i} and θ_{2i} as shown in Fig.3. Then, an intruder whose coordinate is (x, y) is detected by a camera sensor whose coordinate is (x_i, y_i) only if the following two conditions hold true.

(a) Distance Condition

$$\sqrt{(x_i - x)^2 + (y_i - y)^2} \leq r \tag{1}$$

(b) Angle Condition

$$\theta_{1i} \leq \arccos \frac{(x - x_i)}{\sqrt{(x - x_i)^2 + (y - y_i)^2}} \leq \theta_{2i} \tag{2}$$

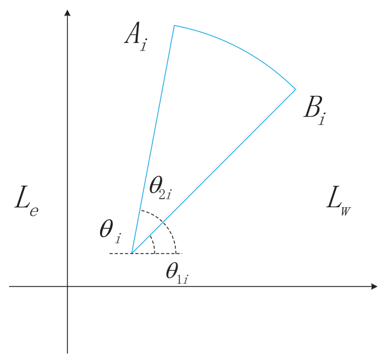

Fig. 3. Definition of θ_i, θ_{2i}, and θ_{1i}, where $\theta_i = \theta_{2i} - \theta_{1i}$.

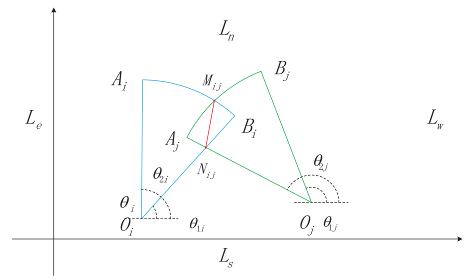

Fig. 4. The two camera sensors are a β-sensor of the other only if the length of the breadth of their sensing sector, which is the line connecting $M_{i,j}$ to $N_{i,j}$, is at least β.

Next, we introduce several important concepts and the formal definitions of our problems of interest.

Definition 1 (Breadth [10])**.** *The breadth of a barrier coverage over an object provided by a camera sensor network refers to the width of the picture of the object taken by the barrier when the object moves through the barrier.*

Remind that as shown in Fig.1, the breadth of a barrier coverage over a moving object provided by a camera sensor network can be significantly different depending on the trajectory of the object.

Definition 2 (β-B^3)**.** *A belt-barrier of camera sensors whose minimum breadth is β is called a β-breadth belt-barrier (β-B^3).*

Definition 3 (β-QoM)**.** *The quality of monitoring (QoM) provided by a β-breadth belt-barrier is β-QoM.*

Definition 4 ((β, 1)-B^{3}CP)**.** *Given a camera sensor network S, the minimum β-breadth belt-barrier construction problem ((β, 1)-B^{3}CP) is to find a minimum subset $S' \subseteq S$ such that S' is a β-B^3 with minimum cardinality.*

Definition 5 ((β, k)-B^{3}CP)**.** *Given a camera sensor network S, the k concurrent β-breadth belt-barrier construction problem ((β, k)-B^{3}CP) is to construct k node-disjoint β-breadth belt-barriers using minimum number of camera sensors.*

IV. A New Polynomial Time Optimal Algorithm for (β, 1)-B^{3}CP

In this section, we describe our polynomial time exact algorithm for (β, 1)-B^{3}CP, namely (β, 1)-B^{3}CA. We will first introduce a set of rules to determine if the breadth of two overlapping sensing sectors is greater than or equal to β. Then, we use these rules to construct (β, 1)-B^{3}CA.

A. Construction of β-sensor List

Let us introduce one important definition, which will be used for the rest of our discussion.

Definition 6 (β-sensor)**.** *Given a sensing sector s_i, another sensor s_j is a β-sensor of s_i only if the minimum breadth of the barrier jointly provided by s_i and s_j is at least β.*

For instance, in Fig. 4, the two camera sensors are a β-sensor of each other if the length of the line connecting $M_{i,j}$ to $N_{i,j}$ is at least β. It is noteworthy that given two overlapping sensors s_i and s_j, the length of the breadth is the length of the shortest line between two intersecting points of the border lines of the sectors s_i and s_j such that one point on the top of the sectors (to which the intruder can move without being detected) and the other point is on the bottom (or side) of the sectors (to which the intruder has to be detected by the sensors).

Based on this observation, let us introduce the set of rules to find the set of β-sensors for each camera sensor. Consider a camera sensor s_i deployed in region R. We can easily obtain the information of its sensing range r and its central angle θ_i, as well as θ_{1i} and θ_{2i} through GPS system, as shown in Fig.4. For the ease of our illustration, we will use Fig. 4 for our discussion. In the figure, the boundary of s_i can be divided into three parts which include two radial edges O_iA_i and O_iB_i, an arc $\widehat{A_iB_i}$. Remind that we know the exact coordinates of O_i, A_i and B_i. Also note that line O_iA_i or O_iB_i may be parallel to the y-axis. Then, there are the following three cases we need to consider for the equations of O_iA_i, O_iB_i, and $\widehat{A_iB_i}$.

(a) **Case 1**: If $\theta_{1i} = \pi/2$ or $3\pi/2$, then $\theta_{2i} \in (\pi/2, \pi)$ or $\in (3\pi/2, 2\pi)$ respectively,

$$\begin{cases} O_iA_i\colon y - y_i = \dfrac{(y_i - y_{Ai})}{(x_i - x_{Ai})}(x - x_i), \\ O_iB_i\colon x = x_i, \\ \widehat{A_iB_i}\colon (x - x_i)^2 + (y - y_i)^2 = r, \\ \qquad \text{such that } (x, y) \text{ satisfies Eq. (2).} \end{cases} \tag{3}$$

(b) **Case 2**: If $\theta_{2i} = \pi/2$ or $3\pi/2$, then $\theta_{1i} \in (0, \pi/2)$ or $\in (\pi, 3\pi/2)$ respectively,

$$\begin{cases} O_iA_i\colon x = x_i, \\ O_iB_i\colon y - y_i = \dfrac{(y_i - y_{Bi})}{(x_i - x_{Bi})}(x - x_i), \\ \widehat{A_iB_i}\colon (x - x_i)^2 + (y - y_i)^2 = r, \\ \qquad \text{such that } (x, y) \text{ satisfies Eq. (2).} \end{cases} \tag{4}$$

(c) **Case 3**: If there are no lines parallel to the y-axis, then

$$\begin{cases} O_iA_i\text{: } y - y_i = \dfrac{(y_i - y_{Ai})}{(x_i - x_{Ai})}(x - x_i), \\ O_iB_i\text{: } y - y_i = \dfrac{(y_i - y_{Bi})}{(x_i - x_{Bi})}(x - x_i), \\ \widehat{A_iB_i}\text{: } (x - x_i)^2 + (y - y_i)^2 = r, \\ \qquad \text{such that } (x, y) \text{ satisfies Eq. (2).} \end{cases} \tag{5}$$

If the sensing sector s_i intersects with the sensing sectors of the other sensors, there can be one or more intersection points between the border lines of the sectors. For example, in Fig. 4, s_i intersects with s_j and there are two end points of intersection, M_{ij} and N_{ij}, which appears on $\widehat{A_iB_i}$ and O_iB_i respectively. Without loss of generality, suppose that s_i's center is O_i whose coordinate is (x_i, y_i) and s_j's center is O_j whose coordinate is x_j, y_j. According to Eq. (3), Eq. (4) and Eq. (5), we can obtain several intersections of the border lines of s_i and s_j. Suppose $\{p_1, p_2, ..., p_k\}$ is the set of those points where $0 \le k \le 9$ as there are 9 points of intersection at most (2 border lines and 1 arc for each sensing sector). Then, the breadth of the barrier cover provided by s_i and s_j is the length of the shortest line connecting a point above the sector and another point which is not on the top. As one sensor may have several β-sensors, let us define the set of β-sensors of a sensor s_i as the β-sensors list of s_i as follows.

Definition 7 (β-sensor list (SL)). *For every sensor $s_i \in S$, each of its neighbors which intersect with the sensor node and the breath between them is not less than β constitutes s_i's β-sensor list denoted by SLs_i, i.e., SLs_i = $\{s_{p_1}, s_{p_2}, ..., s_{p_k}\}$ where $0 \le k \le n$. If $k = 0$, then SLs_i = $\emptyset$.*

Next, let us introduce a polynomial time algorithm to construct SLs_i for each $s_i \in S$ (Algorithm 1). In this algorithm, we assume the camera sensors in S are sorted in ascending order according to s_i's x-coordinate for the sake of easier analysis. Without loss of generality, we add two virtual sensors s_0 and s_{n+1} representing L_w and L_e respectively. To find out all the β-sensors for each sensor node, we can simply choose one sensor s_i and then verify if all the other sensors intersect with s_i and if their minimum breadth is greater than or equal to β. Clearly, the running time of this algorithm is bounded by $O(n^2)$, where $n = |S|$. We would like to emphasize that for each s_i, s_i cannot be used to construct a β-B^3 if $|SLs_i| \le 1$ since a valid member of a β-B^3 should form a chain of sensors from left border to the right border.

Algorithm 1 β**-Sensors Selection** (S)

```
for i = 1 to n do
    //Initialization
    SLs_i = ∅;
    b_i = SLs_i;
end for
for i = 1; i ≤ n; i = i + 1 do
    //Find out every sensor s_i's SL
    for j = 0; j ≤ n + 1; j = j + 1 do
        if i = j then
            continue;
        else
            if s_j intersects with s_i then
                compute their breadth MN_ij//As shown in Fig. 4.
                if MN_ij ≥ β then
                    SLs_i = SLs_i ∪ {s_j};
                end if
            else
                continue;
            end if
        end if
    end for
    b_i = SLs_i;
end for
Return B = {b_1, b_2, ··· , b_n};
```

B. Description of (β, 1)-B^{3}CA

Now, we are ready to describe our strategy to use the β-sensor list for each sensor node in S to solve (β, 1)-B^{3}CP. Once the β-sensor list for each node in S is completed by Algorithm 1, we construct an edge-weighted graph $G = (V, E, w)$. We first set $V \leftarrow S \bigcup \{s_0, s_{n+1}\}$. Also, there exists an edge between s_i and s_j in E only if $s_j \in SLs_i$ (or equivalently $s_i \in SLs_j$). s_0 represents L_w of R and any s_i is connected to s_0 only if the line connecting two intersecting point between the border of s_i and L_w is at least β. Similarly, s_{n+1} represents L_e of R and any s_j is connected s_{n+1} only if the line connecting two intersecting point between the border of s_j and L_e is at least β. Once V and E are determined, we add an edge weight of all edges in E except those edges connecting some s_i to s_0 or some s_j to s_{n+1}. For those exceptional edges, we set the weight of them to be 0.

Once $G = (V, E, w)$ is constructed, we compute the shortest path from s_0 to s_{n+1} which can be done within polynomial time, e.g. Dijkstra algorithm. It is easy to see that

(a) the set of sensors included in the shortest path of length l can form a β-breadth belt-barrier with $l + 1$ sensor nodes, and

(b) the β-breadth belt-barrier computed in this way consists of the minimum number of camera sensors.

V. A New Heuristic Algorithm for (β, k)-B^{3}CP

In this section, we propose a polynomial time heuristic algorithm for (β, k)-B^{3}CP. From the previous section, we learned that given S, a path from s_0 to s_{n+1} in the edge-weighted auxiliary graph $G = (V, E, w)$ implies one β-breadth belt-barrier. Therefore, by computing k (intermediate) node disjoint paths from s_0 to s_{n+1} in G, we can obtain k concurrent node disjoint β-breadth belt-barrier, which is a feasible solution of (β, k)-B^{3}CP.

Using an idea similar to the one in [23], from $G = (V, E, w)$, we obtain another node-weighted auxiliary graph $G' = (V', E', w')$ as follows (see Fig. 5).

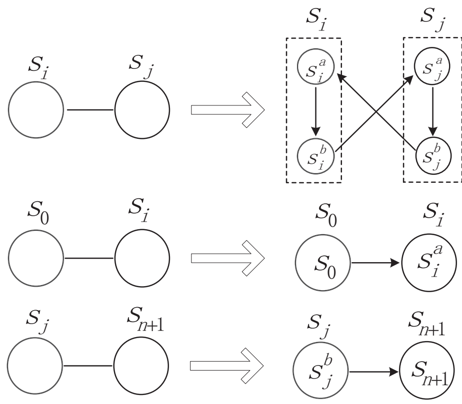

Fig. 5. A node v is divided into v^a and v^b, and necessary links are added to enforce that at most one flow can go through v.

(a) Add s_0 and s_{n+1} to V'. For each node $s_i \in V \backslash \{s_0, s_{n+1}\}$, we add two nodes s_i^a and s_i^b to V'. Then, we add a directed edge from s_i^a to s_i^b into E'. Set the capacity of this edge $cap(s_i^a, s_i^b)$ to 1, and its cost $cost(s_i^a, s_i^b)$ to 1.

(b) For each edge $(s_i, s_j) \in E$ such that neither of s_i and s_j is either s_0 or s_{n+1}, add two directed edges (s_i^b, s_j^a) and (s_j^b, s_i^a). Set $cap(s_i^b, s_j^a)$ and $cap(s_j^b, s_i^a)$ to 1. Set $cost(s_i^b, s_j^a)$ and $cost(s_j^b, s_i^a)$ to 0.

(c) For each edge $(s_0, s_i) \in E$, add a new edge (s_0, s_i^a) to E'. Set $cap(s_0, s_i^a) = 1$ and $cost(s_0, s_i^a) = 0$.

(d) For each edge $(s_j, s_{n+1}) \in E$, add a new edge (s_j^b, s_{n+1}) to E'. Set $cap(s_j^b, s_{n+1}) = 1$ and $cost(s_j^b, s_{n+1}) = 0$.

We claim the (β, k)-B^{3}CP defined over S is transformed into a minimum cost k flow problem from s_0 to s_{n+1} on $G' = (V', E', cap, cost)$. In detail, suppose $f(u, v)$ represents the flow from u to v. The mathematical model of the minimum cost k flow problem is as follows:

$$\min \sum_{(u,v)\in E'} f(u, v) \cdot cost(u, v), \tag{6}$$

such that

$$\begin{cases} f(u, v) \leq cap(u, v), & \text{// Capacity Constrains} \\ f(u, v) = -f(v, u), & \text{// Skew Symmetry} \\ \sum_{w\in V' - \{s_0, s_{n+1}\}} f(u, w) = 0, & \text{// Flow Conservation} \\ \sum_{w\in V'} f(s_0, w) = k \text{ and } \sum_{w\in V} f(w, s_{n+1}) = k & \\ & \text{// Required Flow.} \end{cases}$$

Next, we show the claim it true.

Theorem 1. *The k flows in G' computed by a minimum cost flow algorithm equal to the k node disjoint β-breadth belt-barriers.*

Proof: To prove this theorem, we first prove that from the k flows, we can obtain k node disjoint paths from s_0 to s_{n+1}, which are k node disjoint β-breadth belt-barriers. We also need to prove the cost of the k paths with minimum total cost corresponds to the number of sensor nodes in k node disjoint β-breadth belt-barriers.

Every edge $(u, v) \in E'$ has capacity $cap(u, v) = 1$, and cost $cost(u, v) \in \{0, 1\}$, and flow $f(u, v) \in \{0, 1\}$. Also, the cost between two sub-nodes, s_i^a and s_i^b equivalently is 1. Suppose that $P(s_{n+1})$ is a path from s_0 to s_{n+1}, i.e., $P(s_{n+1}) = \{s_0, \hat{s}_1^a, \hat{s}_1^b, \cdots, \hat{s}_m^a, \hat{s}_m^b, s_{n+1}\}$, and $W_{P(s_{n+1})} = \sum_{(u,v)\in P(s_{n+1})} cost(u, v)$. It is easy to see that $W_{P(s_{n+1})}$ is the number of sensors on the corresponding path in G from s_0 to s_{n+1} since $cost(s_i^a, s_i^b) = 1$ and cost of the other links is 0.

Now, we prove the k paths in G corresponding to the k flows in G' are node disjoint by contradiction. Suppose that flow f_1 and flow f_2 shares one common node ν^b. The node ν^b's direct previous node is ν^a. Thus, the capacity of link (ν^a, ν^b) will have to be 2 to ensure that f_1 and f_2 both flow through node ν^b, which contradicts that the capacity of link (ν^a, ν^b) is 1. It is the same case with that flow f_1 and flow f_2 intersect at a node ν^a.

Next, we prove the cost of the k paths with minimum total cost corresponds to the number of sensor nodes in k node disjoint β-breadth belt-barriers. For a path $P(s_{n+1})$ from s_0 to s_{n+1} in G',

$$\begin{aligned} W_{P(s_{n+1})} = & cost(s_0, \hat{s}_1^a) + cost((\hat{s}_1^a, \hat{s}_1^b)) \\ & + cost((\hat{s}_1^b, \hat{s}_2^a,) + \cdots + cost(\hat{s}_m^b, s_{n+1}). \end{aligned}$$

As the cost of the links (s_i^a, s_i^b) is 1, and the cost of other links are 0, so $W_{P(s_{n+1})} = m$. If we denote the number of sensors involved in $P(s_{n+1})$ as $Num_{P(s_{n+1})}$, we can conclude that $Num_{P(s_{n+1})} = W_{P(s_{n+1})}$. Suppose that the k disjoint paths are $P(s_{n+1})_1$, $P(s_{n+1})_2, \cdots, P(s_{n+1})_k$, then

$$\sum_{1\leq i\leq k} Num_{P(s_{n+1})_i} = \sum_{1\leq i\leq k} m_i.$$

Since $\sum_{1\leq i\leq k} m_i$ is minimum, $\sum_{1\leq i\leq k} Num_{P(s_{n+1})_i}$ becomes minimum, either. As a result, this claim is true. ■

To deal with the minimum cost flow problem, there are a number of classical algorithms such as [14], [21], and [22]. In this paper, we choose He's algorithm[14], which is asynchronous and distributed and takes $O(n^2 log(n))$ messages and $O(n^2 log(n))$ time.

VI. Simulation Results and Analysis

For this section, we provide our simulation result to evaluate the average performance of (β, 1)-B^{3}CA and (β, k)-B^{3}CA. As we discussed earlier, the D-TriB algorithm [10] is the best algorithm in the literature so far for (β, 1)-B^{3}CP in a sensor network of non-adjustable camera sensors. Therefore, we compare (β, 1)-B^{3}CA with D-TriB. To evaluate the average performance of (β, 1)-B^{3}CA, since there is no existing competitor, we compare (β, k)-B^{3}CA with (β, 1)-B^{3}CA. In the simulations, sensor nodes are randomly distributed over a region of size $L \times W$, where $L = 200$ unit distance and $W = 200$ unit distance. Each sensor has a sensing range of

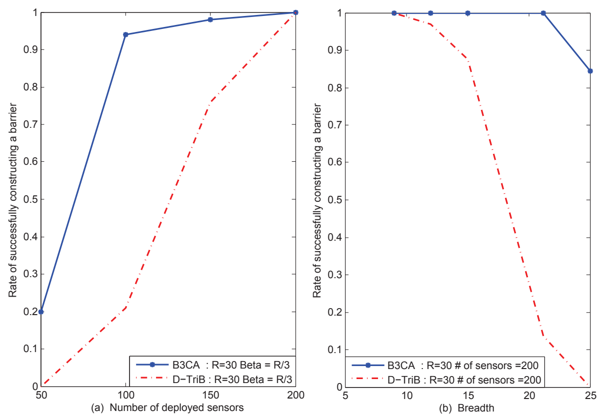

Fig. 6. Performance comparison between (β, 1)-B^{3}CA vs. D-TriB. Fig. (a) shows the change of success rate of building up a barrier while the number of sensors is changing. Fig. (b) shows the change of success rate of building up a barrier while β is changing.

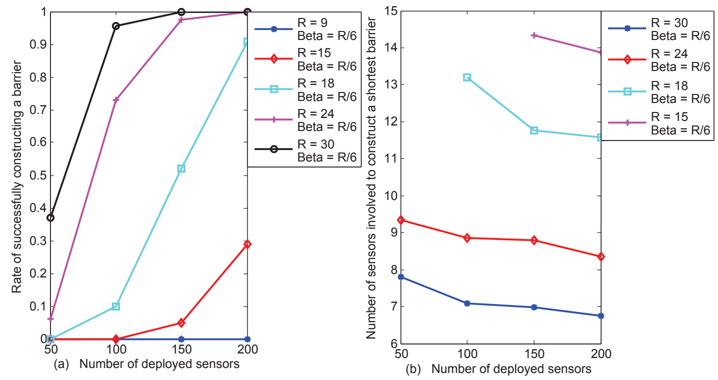

Fig. 7. (a) Success rate vs. number of sensors deployed. (b) Required number of sensors vs. number of sensors deployed.

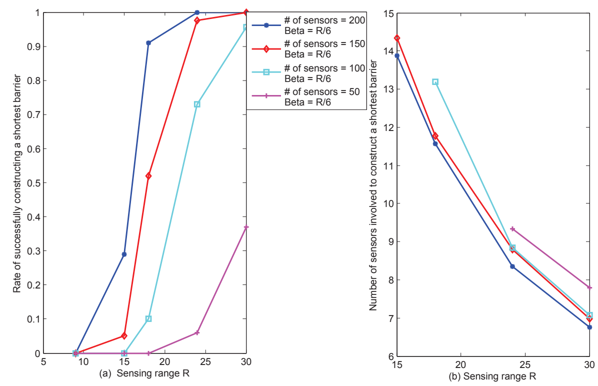

Fig. 8. (a) Success rate vs. sensing range R. (b) Required number of sensors vs. sensing range R.

R and a communication range of $2R$ following our earlier assumption. The field of view of each sensor is denoted by θ and we will vary the minimum breadth β to see its impact. Note that our simulation results are averaged one after 200 repetitions.

A. Comparison of (β, 1)-B^{3}CA and D-TriB

In this subsection, we compare the performance of (β, 1)-B^{3}CA and D-TriB in terms of success ratio, i.e. how many times a β-breadth belt-barrier is successfully constructed under different β and n, the number of sensors. In the first simulation set, we set the sensing range R to be 30 unit, the field of view θ to $\pi/3$ and β to $R/3$. Then, we vary n from 50 to 200. In this subsection, we set $n = 200$, $R = 30$ unit, and vary β to observe the impact of β over the success rate.

From Fig.6.(a) we can learn that as the number of sensor nodes increases, (β, 1)-B^{3}CA (notated by B3CA) is getting better than D-TriB. Roughly, the success rate of (β, 1)-B^{3}CA is 100% higher than that of D-TriB. However, once the area R is fully saturated with sensor nodes (e.g. $n = 200$ within a 200×200 virtual space), their performance becomes similar. Fig.6.(b) shows that how the breadth β impacts the performance of the algorithms. As β increases from 9 to 25, the success rate of D-TriB algorithm starts dropping drastically while (β, 1)-B^{3}CA does it once β becomes 20 at which D-TriB barely succeed in the construction of a β-breadth belt-barrier. Our simulation result clearly indicates that (β, 1)-B^{3}CA outperforms D-TriB, which coincides with the fact that (β, 1)-B^{3}CA is an optimal algorithm.

B. Impact of Parameters over the Performance of (β, 1)-B^{3}CA

In this subsection, we investigate the impact of sensing range R, breadth β, and number of sensors n over the success rate of (β, 1)-B^{3}CA as well as the least number of sensors needed to construct a shortest barrier. The field of view θ of this subsection is $\pi/4$.

First, we set the breadth β to be $R/6$. Then, we vary the sensor's sensing range $R = 9, 15, 18, 24, 30$ unit and the number of sensor nodes $n = 50, 100, 150, 200$. Fig.7 shows that the success rate of constructing a barrier under different number of camera sensors. The percentage increases very quickly as the sensor density increases. We can observe as n increases, it is much easier to build a barrier. Under the condition that $R = 30$ unit and $\beta = R/6$, only 150 sensors can make the successful rate to be 100% while when $R = 9$ and $\beta = R/6$, 200 sensors are not enough to successfully construct a barrier even once. Fig.8 shows that the number of camera sensors required to construct a shortest barrier under different sensing range R. As sensing range R increases, the success rate increases. It can observed that under the condition that $R = 15$, number of sensors = 50 and 100 and the condition that $R = 18$, number of sensors = 50, a barrier cannot be formed. It can be also observed that the larger sensing range R is, the less sensors required to form a shortest barrier.

Second, we set the sensor's sensing range $R = 30$ unit and the breadth $\beta = 9, 12, 15, 21$ unit. Then, we vary $n = 50, 100, 150, 200$. Fig.9 shows that the number of camera sensors required to construct a barrier under different n. It can observed that under the condition that $R = 30$ and $n = 150$,

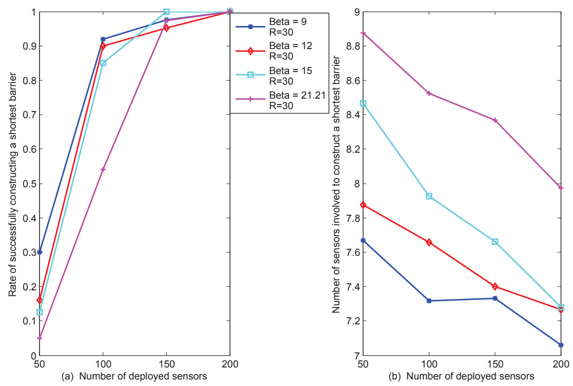

Fig. 9. (a) Successful rate vs. number of sensors deployed. (b) Required number of sensors vs. number of sensors deployed.

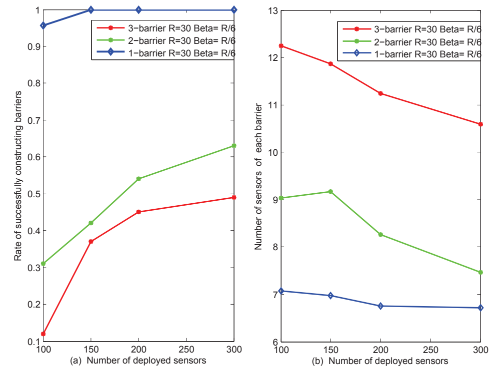

Fig. 11. One-barrier coverage vs. k-barrier coverage. Fig.(a) shows the success rate of building up barriers along with sensor number, $k = 2$ and 3. Fig.(b) shows the average number of sensors in each barrier.

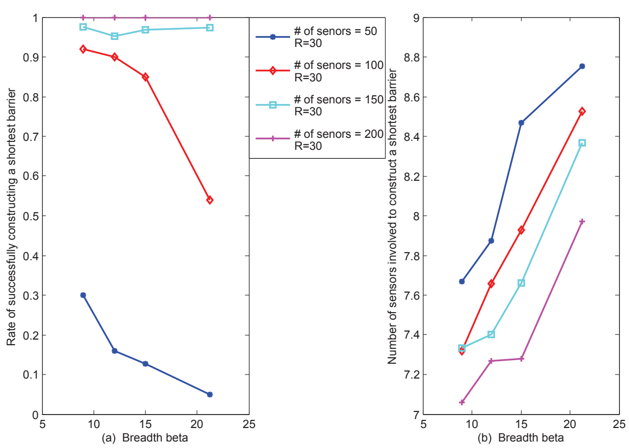

Fig. 10. (a) Success rate vs. breadth β. (b) Required number of sensors vs. breadth β.

the success rate of constructing a barrier increases dramatically from a low level for reasonable breadth and the more sensors deployed, the more likely it will be to form a barrier. It can be derived from Fig.9.(b) that the more sensors deployed, the less sensors required to form a barrier and the larger the breadth is, the more sensors are required to construct a shortest barrier. Fig.10 shows that the success rate of constructing a barrier under different β. The percentage decreases very quickly as the sensor density increases if the number of sensors deployed is not large. It can be observed that the larger β is, the more difficultly it will be to form a shortest barrier. Under condition that $R = 30$ unit and $n = 100$, the success rate drops quickly from a high level to 0.54 as β becomes 21.21 unit. On the other hand, under condition that $n = 150, 200$, the success rates are quite high and do not drops even while β increasing. The reason for this is that the coverage λ is very high as $\lambda = N \times \pi \times R^2/L \times W$ when $R = 30$ and $n = 150, 200$. Thus, there are enough proper sensors to construct a barrier. In fact, when β increases to 25, the successful rate drops quickly for both the conditions that the number of sensors = 150 and 200.

Comparing Fig.8.(a) and Fig.10.(a) , we can find that as breadth β changes from 9 to 21.21, sensors require to construct a barrier range from 7.059 to 8.752 while as sensing range R changes from 15 to 30, sensors required from 6.75 to 14.33. Meanwhile, By comparing Fig.8.(a) and Fig.10.(a), we can find that as breadth β changes from 9 to 21.21, the maximum residual of success rate to form a barrier is 0.38 while as sensing range R changes from 15 to 30, the maximum residual is 0.957. Therefore, we can conclude that sensing range R has more influence than breadth β on both sensors required and the successful rate to form a barrier.

C. Performance for (β, k)-B^{3}CA

In this subsection, we study the performance of (β, k)-B^{3}CA. We set the breadth β to be $R/6$ and the sensor's sensing range $R = 30$ unit to ensure that the construction of k-barriers suing (β, k)-B^{3}CA becomes easier. We vary n to 100, 150, 200 and 300. In this experiment, we vary $k = 2, 3$ to see the impact of barrier on the success ratio.

Fig.11.(a) suggests that the success rate of (β, k)-B^{3}CA (the rate to build k node-disjoint β-breadth belt-barriers successfully) is much lower than that of $(\beta, 1)$-B^{3}CA (the rate to build one β-breadth belt-barrier). On the other hand, Fig.11.(b) shows that the average number of sensors of each barrier involved to construct k barriers are more than those of one-barrier. And as k increases, the success rate decreases while the average number of sensors involved increases. We can conclude that to ensure quality of surveillance, (β, k)-B^{3}CA requires a sufficient number of sensors to be deployed.

VII. Concluding Remarks and Future Work

In this paper, we investigate two optimization problems, namely the minimum β-breadth belt-barrier construction problem ((β, 1)-B^{3}CP) and the minimum β-breadth k belt-barrier construction problem ((β, k)-B^{3}CP). While (β, 1)-B^{3}CP in a sensor network of non-adjustable camera sensors has been investigated in [10], it can produce sub-optimal solutions. In this paper, we introduced a new polynomial time exact algorithm for (β, 1)-B^{3}CP, which produces optimal solutions. Our simulation result shows our algorithm outperforms the solution proposed in [10]. Meanwhile, (β, k)-B^{3}CP is a variation of $(\beta, 1)$-B^{3}CP with a fault-tolerance consideration and is a new problem proposed by us.

In this paper, in the course of studying the problem, we assume there is no obstacle on the area of our interest, which could be considered as a unrealistic assumption. However, even with the existence of some obstacles, our approach can be easily applied by modifying the β-sensor decision algorithm described in Section IV. We present a new heuristic algorithm for (β, k)-B^{3}CP and evaluate its performance via simulation. As a future work, we plan to further investigate a polynomial time exact solution for $(\beta, 1)$-B^{3}CP if any.

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