Bandwidth-aware Breach-free Barrier Construction with VANET nodes for Realtime Fugitive Search

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***Abstract*—In this paper, we introduce a new strategy of using VANET nodes with visual sensors and wireless transceivers to build an instant camera barrier for a given mission period. Given a set of properly equipped VANET nodes whose drivers voluntarily join the protocol by exposing their future travel plans and use onboard equipment to transmit realtime video to the authority, we aim to maintain the barrier of VANET nodes during a given mission period. Under the constraints that the mobility of each VANET node is not controllable and the size of barrier, i.e. the number of concurrent participants, cannot exceed a given number due to the network system capacity limit, we propose a polynomial time algorithm for the problem. To the best of our knowledge, this is the first work to consider the construction of camera barriers in pure mobile camera sensor network.**

***Index Terms*—Sensor barrier, sensor networking, VANET, barrier breach, scheduling.**

I. Introduction

Vehicular ad hoc network (VANET) is a widely used term to refer a wireless network of vehicles. Conceptually, VANET nodes are similar to the ordinary vehicles travelling on the roads and highways or parked in a parking lot or along roadside. However, they are distinguished by the special onboard equipments such as various sensors, computing units, data storages, wireless transceivers, all of which altogether make each VANET node to collaborate with other VANET nodes nearby/remotely and enable a number of innovative applications. In VANET, each node can serve as either an application field information provider (by sensing and/or computing) or an intermediate router to single-hop or multi-hop forward the information to its intended recipient which can be either another VANET node or VANET infrastructure. Currently, VANET is being considered as a platform to enable a wide range of commercial applications such as remote vehicle personalization and diagnostics, Internet access, digital map downloading, real time video relay, and value-added advertisement [1]. Due to the reasons, VANET nowadays attracts much attention from various commercial car vendors such as Ford, General Motors, Toyota, Nissan, Chrysler, and BMW.

Over years, several sensors have been considered for VANET nodes to enable a number of interesting applications. Among those, camera sensors attracted lots of attention as (a) they are currently in use for various vehicles in the form of a black box (also known as dash cam), and (b) they can be used for various purposes such as recording accidents to be used as a legal evidence of court dispute and collecting realtime traffic information for better congestion control. For instance, Gerla et al. [2] proposed a mobile cloud-based scheme called pics-on-wheels (POW) that delivers pictures to the citizens by using vehicles cameras on demand. Hussain et al. [3] has pointed out Gerla et al.'s scheme is lack of proper security mechanism and proposed the concept of vehicle witnesses as a service (VWaaS), which aims to offer a proper privacy preserving mechanism for the providers of visual data, which are VANET nodes on the street which voluntarily join to protocol.

From sensor networking point of view, a VANET node with a visual sensor can be considered as a mobile camera sensor node with wireless transceiver whose trajectory cannot be controlled and who are capable of performing multi-hop routing. In fact, in the previous researches conducted by Gerla et al. [2] and Hussain et al. [3], VANET nodes are conceptually used as such. On the other hand, we observe that while the trajectory of each VANET node may not be easily controllable, its trajectory can be known in advance under a certain circumstance: In 2013, two suspects installed bombs nearby the roadside where many people were watching the Boston Marathon, exploded them, killed fifteen people and more than two hundred sixty people wounded [4]. The suspects fled from the scene along with the terrified crowd. It took several days to obtain pictures from stationary surveillance cameras as well as from the cameras of the tourists leaving nearby airports, analyze them, identify and capture the suspects, who conspired to blast New York Time Square area spontaneously [5]. We observe that this story shows two important points. First, it is highly likely for the driver of each VANET node may disclose their future trajectory for a short time to collaborate with law reinforcement under the extreme circumstance even though their privacy is invaded. Second, under the circumstance,

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VANET nodes with visual sensors are great sources of images to collect realtime information around a crime scene to find and track the potential suspects immediately.

Motivated by this observation, in this paper, we investigate the potential of using VANET nodes with visual sensors and wireless transceivers to form a kind of a camera barrier which surrounds a serious crime scene so that real-time video can be collected by the proper authority given that the future trajectory of each VANET node is known in advance. This system could be useful to identify the moving direction or the location of potential suspects who may try get away from the crime scene on foot or by car. The main contribution of this paper has two folds.

(a) For the first time in the literature, we discuss the idea of constructing camera barrier of VANET nodes, which are essentially mobile camera sensor nodes whose future trajectories are known in advance, but cannot be controlled. We realize that while one easy way to solve this problem is asking every properly equipped (with a visual sensor and a wireless transceiver) VANET node which voluntarily joins the barrier formation to transmit real-time video to the authority concurrently. However, as a wireless network infrastructure always has a limited bandwidth, this may (adversely) result in the temporal communication network black out. Therefore, we aim to achieve our goal by allowing a limited number of VANET nodes to participate the protocol at any moment.

(b) We first construct a graph representing the metropolitan area of interest. Then, we formally introduce our problem of interest, namely the *seamless VANET barrier coverage problem (SVBCP)* over the induced graph. Most importantly, we introduce a polynomial time algorithm for SVBCP, given that the number of VANET nodes participating the construction of the barrier is bounded by a constant, which is related to the network system capacity.

The rest of this paper is organized as follows. Related work is discussed in Section II. The formal definition of our problem of interest, SVBCP, is in Section III. Our main contribution, the polynomail time exact algorithm for SVBCP is in Section IV. Finally, we conclude this paper in Section V.

II. Related Work

In the literature, there are two closely related researches which discuss how to construct a surveillance system using VANET nodes with a visual sensor. In [2], Gerla et al. introduced a mobile cloud-based scheme called pics-on-wheels (POW) that delivers pictures which are taken by onboard cameras to a requester on demand. In this scheme, one can query the cloud infrastructure to obtain a picture of an area of interest. Then, the cloud designates VANET nodes with visual sensors nearby the area to take pictures and send back. In [3], Hussain et al. introduced the concept of vehicle witnesses as a service (VWaaS), which is a visual data collection mechanism based on VANET under some serious event such as a huge accident, riot, or terrorist attack. They pointed out Gerla et al.'s scheme is lack of a mechanism to protect the privacy of the wonder of the VANET node which provides visual data to the central cloud storage per request. To address this issue, in their scheme, the visual data are sent from each VANET node to the cloud infrastructure anonymously. However, for the purpose of using them as evidences for a legal investigation in the future, the privacy protection is conditional and thus can be revoked by authorized entity(s) if necessary.

Conceptually, the VANET nodes with camera sensors can be considered as mobile camera sensor nodes. In the literature, a wireless sensor network is defined to provide barrier-coverage over an area of interest only if any intruder of interest is always detected and notified to a sensor node whenever the intruder passes over the sensor field to trespass into the zone being protected by the sensor network. It is widely believed that the concept of barrier-coverage was originally introduced by Gage [6] in the context of robotic sensors. Over years, the concept of barrier coverage has been investigated extensively [7], [8], [9], [10], [11], [12].

Frequently, the barrier-coverage has been studied in the context of hybrid wireless sensor networks, where a wireless sensor network with static nodes are deployed first and later a set of mobile sensor nodes are deployed to enhance the coverage of the deployed sensor network [13], [23], [15], [16], [17]. For instance, Wang et al. [13] investigated the question of what is the minimum number of mobile sensor nodes to assist a given static ground sensor network to provide k-barrier-coverage. The problem of constructing k-barrier-coverage in a hybrid sensor network with mobile sensor nodes with limited mobility and static sensor nodes was studied by Ma et al. [23]. In [16], Xu et al. exploited mobile sensor nodes to improve the intruder detection ratio of hybrid sensor network. Wang et al. [15] studied how to minimizing the cost to relocate mobile sensor nodes to fill the gap between sensor nodes and form a barrier. Note that our problem of interest is different from those as we are considering the problem of constructing camera barrier in a purely mobile camera sensor network.

Recently, several works have been reported on the coverage issue of camera sensor networks. In [18], Liu et al. introduced a new dynamic node collaboration scheme for mobile target tracking in wireless camera sensor networks. In [19], Devarajan et al. considered a communication network of uncalibrated cameras and proposed a distributed algorithm to achieve comparable calibration accuracy to centralised bundle adjustment. Johnson and Bar-Noy [20] studied the pan and scan problem which aims to configure camera sensors to observe multiple targets under different objectives. Wang and Cao [21] proposed the concept of full-view coverage in camera sensor network, which aims to capture the face of the object of interest regardless of its face direction. The concept of barrier coverage is also widely investigated for camera sensor networks. In [22], Shih et al. discussed how to construct a barrier with static camera sensors. Wang and Cao [21] proposed the idea of full-view barrier coverage, which provide barrier-coverage independent from the face direction of the intruder. In [23], Ma et al. discussed how to construct full-view barrier with the minimum number of camera sensors. Very recently, Xu et

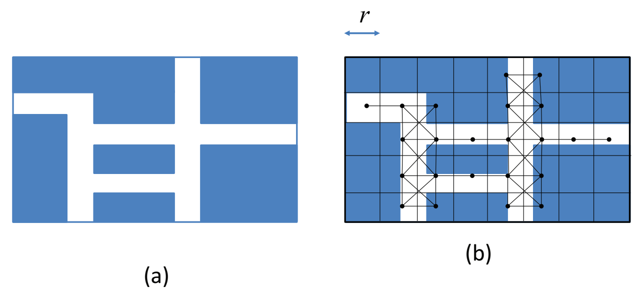

Fig. 1. Abstraction of a metropolitan area map M, e.g. Fig.(a), into a graph, e.g. Fig.(b).

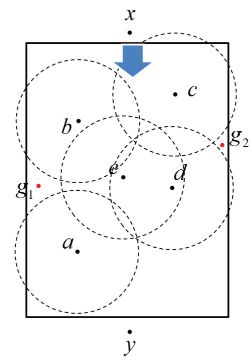

Fig. 2. This figure illustrates the concept of barrier-breach.

al. considered a new barrier-coverage problem under a more sophisticated camera coverage requirement called (k, ω)-angle coverage model (Tseng et al. [24]).

Two Most Relevant Cutting-Edge Results. Liu et al. [25] considered the problem of reinforcing the pre-deployed camera sensor network on grid points with mobile camera sensor network. This work is similar to the existing works in the wireless sensor networks with omni-directional sensing range. As the most of them focused on how to reinforce the barrier-coverage of static sensor networks with several mobile camera sensors, this work is significantly different from our problem. Lee et al. [26] considered the problem of selecting a limited number of VANET nodes among the all VANET nodes moving around a city block which includes the suspects of interest so that the block can be monitored constant. While this work is the most relevant to this work, it is still significantly different from ours as we consider constructing VANET barriers using any vehicles inside the city area rather than only those moving around the block of interest.

III. Problem Statement

In this paper, we study how to select a subset of VANET nodes with visual sensors and wireless connectivity to the central authority, which are either moving on the road and parked on a parking lot, to provide barrier-coverage over an area of interest, which is a huge metropolitan area, for each moment during a give mission period such that any individual (including a fugitive or a suspect) leaving the area has to be observed by a VANET node. We would like to emphasize that

(a) those VANET nodes which do not have a visual sensor and wireless connectivity to the authority, or whose driver does not want to join the protocol to preserve their privacy will be ignored in our computation,

(b) the drivers of the other VANET nodes voluntarily join the protocol to maintain the barrier of VANET nodes to search for the potential suspects so that they has to be observed by at least one VANET node while leaving the scene of crime surrounded by the barrier, and (thus)

(c) the future travel plan (for the next T time units) of each VANET node participating in the protocol is known in advance.

In this paper, we construct a graph to abstract the topology of a metropolitan area. In the following section, we discuss the detail of this construction.

A. Abstraction of Metropolitan Area Topology

In this paper, we assume the shape of the map M of a metropolitan area of our interest is a rectangle. We partition M into regular squares whose length and width are r. Here, r is a user parameter to make the trade-off between the complexity and precision of the proposed strategy. Now, we represent each grid square as a point and obtain a set of grid points representing the whole map. Finally, we construct a topology graph $G = (V, E)$ such that V is the set of central points of the grid squares. For each pair of points $u, v \in V$, $(u, v) \in E$ if the two squares, whose central points are u, v, are adjacent in M. For instance, given a city map in Fig. 1(a), we obtain the abstract graph in Fig. 1(b). From now on, we assume that a given mission period is divided into T consecutive time units and at each moment, each VANET node is on a grid point.

B. Breach of Sensor Barrier

In [27], Kim et al. introduced a security problem in barrier-coverage of wireless sensor network called 'breach'. To maximize the lifetime of barrier-coverage of wireless sensor network, most existing strategies such as [11] first divide a given set of sensor nodes into the maximum number of node-disjoint subsets such that each subset can form a sensor barrier meeting a given coverage requirement. Then, each subset is employed one by one to provide continuous barrier coverage over the area of interest. However, Kim et al. found that when one qualified subset is replaced by another qualified one, still there could be more than one location which can be exploited by a suspect to trespass without being detected by either of the subset even though each of the subset can form a seamless barrier over the area of interest. For instance, in Fig. 2, each of $B_1 = \{b, d\}$ and $B_2 = \{a, c, e\}$ can form a seamless sensor barrier which is capable of detecting any intruder from x to y. However, g_1 and g_2 can be utilized to penetrate the barrier when B_1 and B_2 are alternatively used, and g_1 and g_2 are the breaches of the sensor barrier.

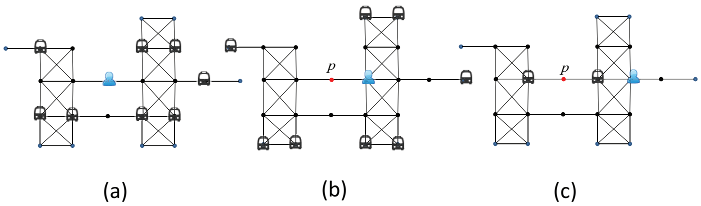

Fig. 3. Breaches may exist as time goes by in the barrier-coverage of VANET nodes.

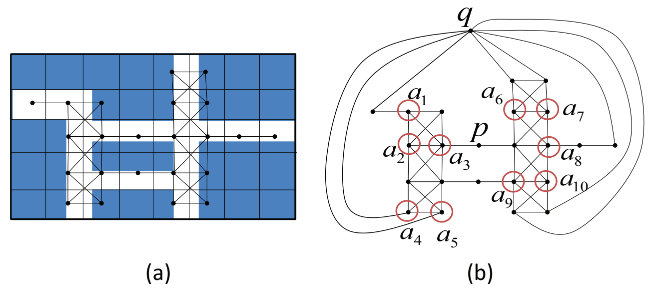

Fig. 4. Given a graph, we construct G', by adding two nodes p and q, each of which represents the initial location of the suspects and the outside area of the city. Clearly, p will be on one of the nodes in G. q is connected to any node in G, which is connected to outside the city. If there exists a path from p to q without passing over any VANET node in the barrier, then the barrier is flawed.

Unfortunately, a barrier-breach-related issue certainly exists in the context of our problem of interest. For instance, consider Fig. 3 in which the suspect is initially on the center node p. As time goes by (from Fig. 3(a) to Fig. 3(c)), each VANET node moves and a different subset of VANET nodes constructs a barrier surrounding p. Despite fact that p has been always surrounded by a subset of VANET nodes, as we can see from Fig. 3(b) and Fig. 3(c), the suspect can stay at a location (e.g. the location of the suspect in Fig. 3(b)) for a moment and get out of the barrier of VANET nodes without being detected (by coincident or by planning). Therefore, the breach of a sensor barrier is still a significant issue to maintain a reliable barrier coverage with VANET nodes over time.

C. Formal Definition of Problem

Now, we formally introduce the definition of our problem, namely the seamless VANET barrier coverage problem (SVBCP). For the ease of understanding our definition, we list some important notations and their meaning. Note that some of the notations are newly defined here. $G = (V, E)$ is a given topology graph, where $V = V(G)$ and $E = E(G)$ are corresponding node sets and edge sets, respectively. T is a given mission period. We assume that in total m VANET nodes will voluntarily participate the protocol and use $A = \{a_1, a_2, \cdots, a_m\}$ to denote the set of participating VANET nodes. For each $a_i \in A$, $L_i^t = (x_i^t, y_i^t)$ will be used to denote the location of a_i at the t-th unit moment from the initiation of the protocol. $L_i = \{L_i^0, L_i^2, \cdots, L_i^T\}$ will be used to denote the location information of a_i during the whole mission period. Note that a_i may not be in the metropolitan area at some moment during the mission period. We denote $L = \{L_1, L_2, \cdots, L_m\}$. Last, b represent the number of VANET nodes which can be included in one barrier at unit moment due to the network system bandwidth limitation in the area, which is usually the bandwidth of the bottleneck from each VANET node to the central authority.

Definition 1 (Seamless VANET Barrier Coverage Problem (SVBCP))**.** *Given a topology graph G, the number T of unit times within a whole mission period, the travel plan of all VANET nodes L during T, and the size limit b of VANET barrier at any moment, the seamless VANET barrier coverage problem (SVBCP) is to find a collection of subsets of VANET nodes $\mathcal{B} = \{B_0, B_1, \cdots, B_T\}$ such that*

(a) the size of each barrier at any moment does not exceed b, i.e. $|B_i| \le b$ for each $B_i \subseteq A$, and

(b) there exists no breach between two consecutive barriers B_i and B_{i+1} for each $i \le T-1$.

IV. Main Contribution: Polynomial Time Algorithm for SVBCP

Now, we are ready to describe our polynomial time exact algorithm for SVBCP. Roughly speaking, we obtain the algorithm by answering the following three key questions.

(a) Question 1: Given a city map abstraction $G = (V, E)$, the initial suspect location p, and a subset of nodes B_i (the locations of participating VANET nodes at the moment i-th unit time), how to determine if B_i provide a barrier coverage over G?
(b) Question 2: Given a $G = (V, E)$ and two barriers B_i and B_{i+1}, how to determine if there is no breach when B_i is replaced by B_{i+1}?
(c) Question 3: How to design a polynomial time exact algorithm of SVBCP?

In detail, we first discuss how to deal with Question 1 in Section IV-A. Then, we use this result to answer Question 2 in Section IV-B. Finally, the results from Section IV-A and Section IV-B are used to design the algorithm in Section IV-C. Later, we also prove that the running time of the algorithm is polynomial and it produces an optimal (best possible) solution.

In this paper, we assume that there are sufficient number of VANET nodes on the street to maintain a seamless barrier over the mission period T. However, this does not mean that such construct is trivial as shown in Fig. 6, a series of wrong choices to select a subset of nodes to construct a barrier for each time unit may result in the situation that the barrier cannot sustain anymore, e.g. there exists a temporal hole in the barrier.

A. How to Check the Integrity of a VANET Barrier

In this section, we propose a simple graph induction strategy for G so that an existing polynomial time exact algorithm for an existing path computation problem such as Dijkstra's shortest path algorithm can be used to determine if a subset B_i of nodes can provide a barrier coverage such that the direction of each VANET node is from outside to inside toward p. For

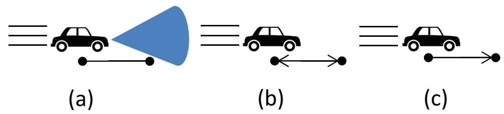

Fig. 5. Each VANET node has a direction on the road at each unit time, e.g. Fig.(a). Therefore, each edge on G can be used by two different VANET nodes toward opposite directions, e.g. Fig.(b). For each node, as we know their direction, any suspect coming toward the VANET node will be taken by the camera on the VANET node.

this purpose, given a G and $p \in V(G)$, which represents the original location of the suspect(s), we add one more node q, which represents the area outside the metropolitan (see Fig. 4). Let us denote the modified graph by G'.

Now, we consider each edge in G' as directional edges. For a node v in B_i, we remove an incoming edge from v's neighbors u to v if any suspect from u to v will be captured by the camera on the VANET node on v (see Fig. 5). This is possible to predict as each side of the road has a direction, and we know where each VANET node is heading to. Suppose this modified direction graph as G'_{B_i}. Finally, we compute a path from p to q in G'_{B_i}. Clearly, if there is no such path, then B_i is a flawless barrier.

B. Barrier-Breach between Two VANET Barriers during Mission Period

Next, we discuss how to determine if there exists a breach when a node subset B_i is replaced by another node set B_j. We first apply the algorithm from the previous section to check if each of B_i and B_j is a flawless barrier. In essence, by the construction, a grid point $w \in V(G) \setminus (B_i \bigcup B_j)$ is a breach only if w is surrounded by B_i, but not surrounded by B_j.

Based on this observation, we first obtain a subset of nodes X which are surrounded by B_i. For this purpose, we can simply compute a path from for each $x \in V$ to q in G'_{B_i}. If no such path exists, add x to X. Then, for each $x \in X$, we check if there exists a path from x to q in G'_{B_j}. Clearly, if no such path exists, then there exists no breach when B_i is replaced by B_j.

C. Scheduling Subsets for Breach-free Barrier

Now, we discuss how to obtain exact solutions of SVBCP based on our results for Question 1 and Question 2 presented in Section IV-A and Section IV-B, respectively, within polynomial time. Based on our discussions so far, to solve SVBCP, we need to construct a sequence of flawless barriers for each unit time during the mission period T.

(a) Suppose S_i is the set of flawless barriers available at i-th moment. To construct S_i, we first pick a node set B out of the set A of available VANET nodes at their corresponding locations at i-th unit moment such that the size of B is 1 to b from G as the size of each barrier cannot exceed the size constraint b. Clearly, all possible cases for B is bounded by $\binom{m}{b} = O(m^b)$. To see if B can form a flawless barrier, we can use the strategy discussed in Section IV. If so, add B to S_i.

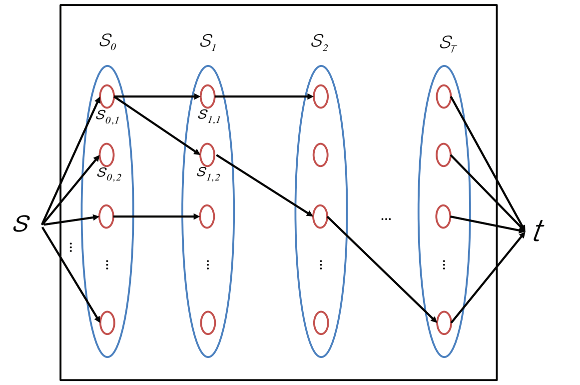

Fig. 6. There is a way to construct a flawless barrier during a mission period T with a set A of mobile VANET nodes whose mobilities are not controllable, if there exists a s-t path in this induced graph $\hat{G}$.

(b) Once S_i is constructed for each $0 \leq i \leq T$, we form an induced graph $\hat{G}$ as follows. First, we add two new nodes s and t. Establish a directed edge from s to all nodes in S_0 and a directed edge from each node in S_T to t. For each node $S_{i,u} \in S_i$ and $S_{i+1,u} \in S_{i+1}$, we add a directed edge from $S_{i,u}$ to $S_{i+1,v}$ only if there exists no barrier breach when the barrier formed by $S_{i,u}$ is replaced by the barrier formed by $S_{i+1,v}$.

(c) Apply a path computation algorithm to find a path from s to t in $\hat{G}$. Suppose $\mathcal{S} = \{S_{0,v_1}, S_{0,v_2}, \cdots, S_{0,v_T}\}$ is the sequence of the intermediate nodes in this s-t path. Then, this is the final output of our algorithm.

Now, we have the following theorem.

Theorem 1. *The proposed strategy solves the SVBCP correctly.*

Proof. We show our strategy can find a solution to SVBCP whenever there is one. Suppose that $\mathcal{B}^* = \{B_0^*, B_1^*, \cdots, B_T^*\}$ is a set of seamless barrier coverage with prescribed property. By our construction of graph $\hat{G}$, it is clear that each $B_i^* \in S_i$ for $i = 1, 2, \cdots, T$. Therefore there always exists a directed path from s to t in graph $\hat{G}$. Thus, by using any Shortest Path algorithm (such as Dijstra's Algorithm), we can always find a directed path, say $B_0 B_1 \cdots, B_T$, from s to t in $\hat{G}$ (not necessarily to be $B_0^* B_1^* \cdots B_T^*$). Again by our construction, $\mathcal{B} = \{B_0, B_1, \cdots, B_T\}$ is the required solution to SVBCP. □

Theorem 2. *The running time of the proposed algorithm is polynomial.*

Proof. At each time $i = 0, 1, 2 \cdots, T$, we construct a subsets S_i which consists of all barrier coverage with at most b available VANETS choosing from m available ones. So the cardinality of S_i is at most $\binom{m}{b} = O(m^b)$. It takes time $O(n^2)$ for checking the flawlessness of each barrier coverage by Dijstra's Algorithm, and so it takes time $O(m^b n^2 T)$ in total to construct all S_i, for $i = 0, 1, \cdots, T$.

For each pair of $S_{i,u}$ and $S_{i+1,v}$, the checking for seamlessness from $S_{i,u}$ to $S_{i+1,v}$ takes time $O(n^3)$ by using Dijstra's

Algorithm, so the construction of the edges of graph $\hat{G}$ takes time $O((m^b)^2Tn^3)$ and hence, the construction of graph $\hat{G}$ takes time $O((m^b)^2Tn^3) + O(m^bn^2T) = O((m^b)^2Tn^3)$. Then finding a path in $\hat{G}$ from s to t takes time $O((m^bT)^2)$ if Dijstra's shortest path computation algorithm is used. Thus, the total time complexity of our algorithm is $O(m^{2b}T^2 + m^{2b}Tn^3)$, which is polynomial in m, n and T, given a fixed b. $\square$

V. Concluding Remarks

This paper makes the first attempt in the literature to construct and maintain a barrier of purely mobile camera sensors over a given mission period. As far as there is a way to do this, our algorithm is able to find it within polynomial time. As a future work, we are interested in designing a faster algorithm for the problem which does not use the enumeration technique that we exploited in this paper. We are also planning to study the problem in the hybrid mobile camera sensor network as there may exists a few fully controllable VANET nodes such as patrol cars in some cases.

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