UDiPP: A Framework for Differential Privacy Preserving Movements of Unmanned Aerial Vehicles in Smart Cities

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***Abstract*—Thanks to recent enormous advance of mobile and vehicular technology, it is highly expected that unmanned aerial vehicles (UAVs) are used for various applications in smart cities as well as the number of flying UAVs in the sky is increasing explosively. However, such a proliferation of UAVs accompanies additional critical issues to be considered for efficient, secure use of UAVs. One of important issues should be the privacy of people. When the UAVs fly to perform specific objectives, minimizing movements of UAVs is an important issue to minimize mission completion time and to maximize the network lifetime of UAVs. To do so, one intuitive solution is that UAVs may pass through private area of citizens whereas people do not want any penetration into own area without a permission. For those situations, we may take into account a compromise so that people can decide whether they give a differential, temporal permission for each UAV to access their areas depending on specific benefits by use of UAVs or emergent situation for public safety. In this study, we introduce a framework for privacy preserving movements of UAVs with differential UAVs' permissions given by citizens, which is called as UAVs' differential privacy preserving movements (UDiPP). Then, using integer linear programming, we formally define a problem whose objective is to minimize total movements of UAVs with preserving privacy of citizens. To solve the problem, we propose a novel approach with a creation of UDiPP graph and then evaluate its performance through extensive simulations.**

***Index Terms*—UAVs, privacy, movements, differential, permission.**

I. Introduction

RECENTLY, Unmanned Aerial Vehicles (UAVs) based on advanced mobile and vehicular technology have come into being as one of emerging next generation technologies because UAVs can be applied to numerous applications which are able to bring convenient, rich and secure life of people. Essentially,

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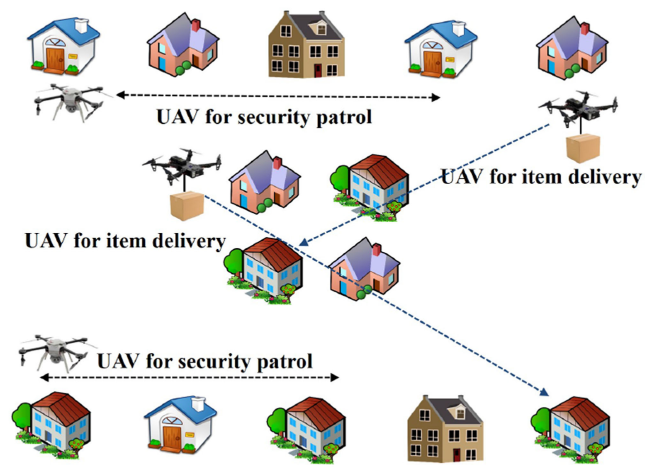


Fig. 1. An example of UAV application.

UAVs are integrated devices with an advanced combination of fundamental body, power supply, thermal sensors, camera with night vision, actuators, etc. Based on the updated technology, UAVs have solid advantages and capabilities such as rapid movement, monitoring harsh environment with reduced cost, a construction of dynamic communication infrastructure, etc. It follows that such advantages allow UAVs to be utilized for critical applications with several objectives such as border patrol and surveillance, wildlife tracking, search and rescue operation of disaster region, intelligent transportation in urban environment, delivering items in both harsh environment and civil area [1], [2], [4], [5]. Initially, a single large UAV was developed for the surveillance purpose. However, as time went by, the use of multiple small-scale UAVs (called as drones) is considered since multiple UAVs have more advantages for scalability, cost efficiency, mission completion time than single large UAV [6]. Hence, it is highly anticipated that an explosive increase of the number of multiple small-sized UAVs in the air will happen in both urban area and extensive ocean [7], [8]. Fig. 1 depicts an example of application for purpose of item delivery and security patrol by multiple small-sized UAVs.

To support successful applicability of UAVs, there are time sensitive issues in the system with UAVs including minimizing total movement distance of UAVs, minimizing maximum distance of UAVs, minimizing mission completion time by UAVs, etc [9]. In particular, the system with multiple small-sized UAVs should be considered carefully to handle those time critical issues because the small-sized UAV has a limited flight time [10], [11] and those limitations may affect the performance of the whole UAV system.

The use of multiple UAVs and its proliferation have prominent advantages for daily life of citizens. But, the dramatically increased number of UAVs in urban circumstance will bring about problematic issues that should be discussed and be handled significantly [12]. In particular, a privacy for people should be highlighted as one of those critical issues. Currently, UAVs have been complained for violation of privacy as well as have been used as a tool of crime [13]. Due to the time-sensitive property of UAV missions, it is anticipated that, in the air, there are a large number of small-sized UAVs that are operated by individuals, industrial companies, government institutions, public communities and the small-sized UAVs will fly with relatively low altitude (ex. The altitude of UAVs by authorized operator should be no more than 400 feet) by regulations of Federal Aviation Administration (FAA) [7]. Also, because small-sized UAV intrinsically includes an equipped camera which can take images and record the monitored information [1], [2], citizens in urban environment will face a security risk with unwanted disclosure of private life whenever UAVs in the air trespass into private regions and properties of people so as to achieve time-sensitive missions. Therefore, unauthorized flights of UAVs over private area should be prohibited strictly or the issue dealing with violating privacy of people should be addressed importantly. On the other hand, it is possible that citizens may allow UAVs to pass through their private areas if they understand the indispensable penetrations of UAVs to fulfill specific missions for public emergent services such as detecting and reporting of emergent disasters including fire, traffic accident, inundation, identifying criminal scene, tracking fugitive, etc. Moreover, it is feasible that people can selectively give permissions into own private areas if they agree and take any profit by allowing those penetrations of UAVs for a specific community or company. (i.e. temporal allowance of delivering UAVs with ordered items). So, it is indispensable to design a new infrastructure in order to support the privacy of citizens and to satisfy the time-sensitive missions by multiple small-sized UAVs simultaneously.

Based on the above motivations, we introduce an infrastructure to support privacy preserving movements of multiple UAVs by considering differential permissions. Then, our contributions of the work can be summarized as follows.

- We introduce a new framework to support privacy preserving movement strategies of small-scale multiple UAVs by considering differential permissions for the UAVs with different operators.
- With the definition of system components including a group of citizens, a set of UAVs, a set of public locations, we show how UAVs are able to do privacy preserving movements with the detection of privacy violation based on practical scenarios. Also, we transform those components into a graph model.
- We formally define a *MintUDiPP* problem whose objective is to minimize total movements (or total flying distance) of multiple UAVs with differential permissions based on the graph model using Integer Linear Programming (ILP).
- Different from our previous work [3], novel approaches including a creation of *UDiPP graph* are developed with the updates including initial setup so as to solve the defined problem. Also, we thoroughly evaluate the performance of the proposed scheme with extensive simulations based on practical and various scenarios.

The rest of paper is organized as follows. A brief presentation of related works is in Section II. Section III describes the proposed system model and scenarios. In Section IV, we not only introduce a framework to support differential privacy preserving movements of UAVs but also formally define a *MintUDiPP* problem. In Section V, the novel approaches with a creation of *UDiPP graph* are proposed to solve the defined problem. Then, in Section VI, we evaluate the performances of the proposed schemes through extensive experiments and complexity analysis. Finally, we summarize the main contributions of this paper and suggest future work in Section VII.

II. Related Work

To deal with various critical issues in UAV networks, there are numerous works studied by researchers. First of all, coordinations of multi-vehicles and future challenges have been addressed previously. In [14], Gancet *et al*. focused on a classical traveling salesman problem setting is utilized to make decisions considering various levels of autonomy of multiple UAVs. Lacroix *et al*. [15] designed a novel model that achieves the deployment of a fleet of heterogeneous UAVs with operational autonomy. Also, for search and rescue missions, Scherer *et al*. [11] developed a modular framework to create a distributed autonomous system considering a coordination of multiple small-sized UAVS. Then, Zeng *et al*. [16] considered an overview of UAV-aided wireless communications that covers on-demand systems consisting of low altitude UAVs that support fast deployment, flexible reconfiguration. Also, in [17], [18], Kim *et al*. introduced an infrastructure to build collision-free reinforced barriers using multiple UAVs, which guarantees to detect various penetration types into the given area.

Besides, many researchers focused on planning trajectory of UAVs. Bertsimas *et al*. [19] proposed a model which considers not only the capacities at the airports but also the capacities of the National Airspace System (NAS) and they showed that the air traffic flow management problem (TFMP) is NP-hard. Then, in [20], Szczerba *et al*. proved that UAV path planning problem is NP-complete and proposed a new route planning model to construct mission-adaptable trajectories. Then, Singh *et al*. [21] developed a model predictive control scheme which navigates UAV with nonlinear dynamics using a vector of pre-determined way-points. Richards *et al*. [22] designed an approximate architecture for aircraft dynamics based on linear constraints with aircraft conflict avoidance. Nikolos *et al*. [23] proposed an evolutionary approach for autonomous UAVs in order to solve two issues: UAV navigation based on an offline planner with a known circumstance and UAV navigation based on an online planner with unknown information. And, to support task assignment and path planning in a dynamic circumstance, Moon *et al*. [24] introduced a hierarchical architecture that is performed by an intersection-based path generation scheme and a negotiation-based task assignment of multiple UAVs with fixed wing. In [25], Besada-Portas *et al*. compared the planners performance by the combined use of several general and problem-specific quality indexes. Also, Ergezer *et al*. [26] focused on solving a path planning problem whose objective is to maximize the collected information from target areas satisfying the condition that a flight into restricted region is prohibited. Furthermore, Zhang *et al*. [27] not only formally defined a global route planning problem of multiple UAVs in 3D circumstance also introduced an improved constrained differential evolution algorithm. Then, Yang *et al*. [28] proposed a UAV path planning scheme based on separate evolution scheme which considers that the way-points of candidate trajectories are found separately. Chen *et al*. [29] devised a dynamic path-planning scheme of UAV routing, which considers a hybrid version for tangent vector field guidance algorithm and Lyapunov vector field guidance algorithm. In [30], Lehouillier *et al*. formulated the new air-traffic collision detection and resolution problem. Authors created a graph whose vertices correspond to discretized values of aircraft and whose edges link collision-free aircrafts. Then, in [31], Sanchez-Garcia *et al*. proposed an intelligent approach based on Jaccard distance and artificial intelligence algorithm. Also, in [32], Akbas *et al*. took into account in actor positioning issue for UAV networks, which supports 3D coverage such that each actor UAV is connected to the central UAV by new practical scenario. Then, in [33], authors studied the resource allocation problem for UAV-assisted networks. Also, they pointed out that the behavior of every device-to-device pair at each time slot is exclusive as well as showed that the proposed problem can be converted into the a mixed integer nonlinear programming.

On the other side, privacy issues in UAV system are addressed in [34]–[37]. Those studies emphasize that UAVs may have critical privacy challenges because they have capabilities to collect information based on the equipped sensor and video camera on board of UAVs. Also, it is possible for UAVs including the collected information to be hijacked by attackers, which will also cause an interruption of the service they perform. In particular, in [38], authors described a laboratory study with various participants who interacted with a real drone to derive use perceptions of privacy and security issues by both real interviews by participants and practical experiments.

III. System Model and Scenarios

In this section, we describe our system model of UAVs including notations, assumptions, system settings which are used in the paper. Then, practically applicable scenarios in the proposed architecture are depicted both with a plan view and with an elevation view.

A. Notations

We first summarize the notations and their descriptions in the Table I.

TABLE I
NOTATIONS

notations	description
A	a two-dimensional square-shaped interested area
U	a set of UAVs
k	the number of UAVs
u_i	a UAV with an identifier i, where $i \leq k, u_i \in U$
C	a set of customers to be visited
n	the number of customers
c_i	a customer i, where $i \leq n, c_i \in C$
P	a set of public points in the public area
q	the number of public points
p_i	a public point i, where $i \leq q, p_i \in P$
T	a set of trespasser (or mission) types
m	the number of trespasser types
t_i	a trespasser type i, where $i \leq m, t_i \in T$
U_{t_i}	a set of UAVs included in a trespasser type t_i
U_{loc}	a set of current location information of UAVs
C_{t_i}	a set of customers who allows t_i
$C_{\neg t_i}$	a set of customers who do not allow t_i
$R(i, j, u_f)$	a route of u_f from i to j, where $i, j \in C, P, u_f \in U$
R	a set of of routes
$EucDist(a, b)$	a euclidean distance between a and b
D_{ind}	an indicator of privacy violation detection
l_{vs}	a length of line segment in virtual square
U_{tmd}	a total movement distance of UAVs
h_{acc}	a height of UAV at an access mode
h_{pre}	a height of UAV at a preserving mode
d_{pub}	a distance of the path using public points
d_{mod}	a distance between h_{acc} and h_{pre}
$\mu_{i,j}$	a distance from location of u_i to customer c_j
$W_{i,j}$	an integer variable of movement between u_i and c_j
$X_{i,j}$	an integer variable of privacy violation
$Y_{i,j}$	an integer variable of public path use
Z_j	an integer variable of the visited customer c_j

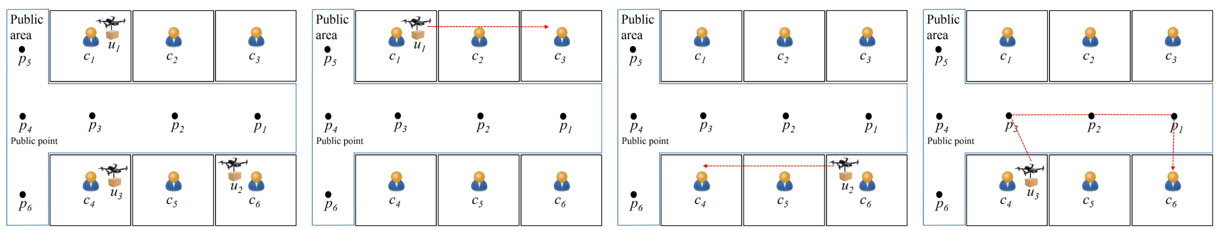
B. Assumptions and System Setting

Our assumptions basically follow FAA's regulations [7] for UAV's operation rules, properties, specifications. Now, we state assumptions for the execution of the proposed system as follows.

- We consider a square-shaped area as a region of interest (ROI) including private area and public area.
- A private region of each customer is a square-shaped area where the customer is at the center of the square and any event within the square is sensed by a pre-installed sensor on the ground.
- The proposed system utilizes multiple small-sized UAVs where each UAV is only operated by one owner.
- Each UAV is equipped with a camera sensor and is capable of taking multiple items with light weight.
- Each UAV has an equal moving speed in the air. (It is no faster than 45 m/s (or 100 mph).
- A straight line-based movement is considered for every UAV.
- The maximum flight altitude of each UAV is no more than 120 meters (or 400 feet).
- Each UAV flies with two modes of altitude: an accessible mode over a permitted private area (i.e. 5 meters) and a preserving mode over an unpermitted private area and a public area (i.e. 120 meters).
- A distance between neighboring public points in the public area is equal.

TABLE II
COMPARISON OF KEY COMPONENTS AND PROPERTIES

Components and properties	Our proposed framework	Other relevant works
Single UAV or multiple UAVs	- Multiple UAVs are utilized.	- A single UAV is used in [28]. Multiple UAVs are used in [23], [24].
Private and public area	- Both private area and public area are defined clearly with different permissions.	- Privacy issues are considered in [34], [35], [36]
Differential privacy preserving	- Differential privacy preserving movement of UAVs are performed where each UAV has two modes: accessible mode and preserving mode.	- Other relevant works do not cover the issue.
Two or three dimensional area	- Two dimensional area is given as RoI.	- Three dimensional area is given as ROI in [27], [32].
UAV movement type	- A straight line-based movement for UAV is scheduled between target points.	- Nonlinear dynamic using a vector of pre-determined way-points is scheduled in [21].



(a) Initial status (b) Movement scenario 1 (c) Movement scenario 2 (d) Movement scenario 3

Fig. 2. Various movement scenarios of UAVs with a plan view.

- The private area of each customer (or citizen) is connected with at least one public point in the public area.

According to the above notations and assumptions, for setting up, our system considers a square-shaped area A. Within A, a set of customer locations C with the size of n and a set of public points P with q numbers in public area are included. There is a set of trespasser types (or mission types), T with the size m. A set of UAVs U with k number of UAVs have initial locations where each UAV is located at the customer position allowing the UAV or is positioned at the public point within public area and each UAV basically has the equal resource and moving speed in the system. Also, the distance between neighboring customers is different but a distance between two neighboring public points is same, which is denoted as d_{pub}. Then, our system considers that each UAV is capable of mode transitions between access mode and preserving mode. When UAV has access mode over permitted private area, it has a low altitude (or height) denoted by h_{acc}. On the other hand, if UAV flies over unpermitted private area and public area as a preserving mode, it has relatively high altitude denoted by h_{pre} and the movement distance between h_{acc} and h_{pre} is represented as d_{mod}. It is highly reasonable that we define two different areas: private area and public area. It follows that there can be two types of UAV waypoints: customer points in privacy area and public points in public area. Citizens can selectively give permissions into own private areas if they agree and take any benefit by allowing those penetrations of UAVs for a specific community or institution. Table II describes the comparison of key components and properties in our system with other relevant works.

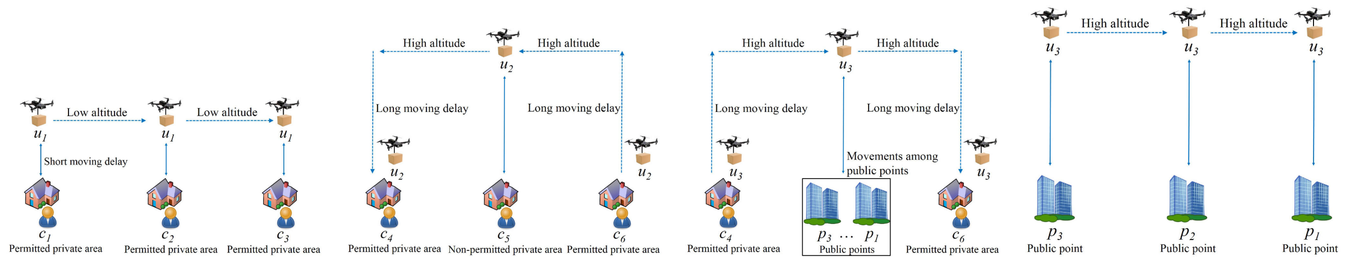
C. Applicable Scenarios With a Plan View

We describe possible movement scenarios by UAVs, which can be executed within possible applications in the paper. Then, suppose that we consider a delivery application by multiple UAVs within the given square-shaped area A that covers public area P and customers' locations C as it can be seen in Fig. 2. The public area P can be accessible by any UAVs with preserving mode and P is composed of several public points: $P = \{p_1, p_2, p_3, p_4, p_5, p_6\}$. The customer area C consists of six customers: $C = \{c_1, c_2, c_3, c_4, c_5, c_6\}$. UAVs can visit customer area C as access mode if they have access permissions given by those customers. Otherwise, UAVs may pass through C with preserving mode. In Fig. 2, let us assume that we have a set of UAVs $U = \{u_1, u_2, u_3\}$ operated by three different industrial companies or different trespass types $T = \{t_1, t_2, t_3\}$ where each UAV is only controlled by the related company. It follows that u_1 is handled by t_1, u_2 is controlled by t_2 and u_3 is operated by t_3, respectively. Moreover, we note that each UAV can not penetrate into the location of customers as access mode without the permission of customers since such a illegal penetration will cause privacy violation of customers.

According to these settings, suppose that c_1, c_2, c_3, c_5 have a membership of the company t_1 and also c_4, c_6 have a membership of both t_2 and t_3. Currently, u_1 flies over c_1 with an access mode. Also, u_2 is located at c_6 and u_3 flies over c_4 using access mode. Fig. 2(a) shows the initial status.

First, let us consider a scenario 1 in Fig. 2(b) where u_1 tries to deliver an item to c_3 from current location c_1 with a height of h_{acc}. To deliver the item handled by t_1, u_1 will consider a short-cut route from c_1 to c_3 by passing through c_2. Because c_2 is a member of t_1, c_2 is willing to permit the penetration of u_2 with a low altitude as h_{acc} into own private area. Hence, as it can be seen from Fig. 2(b), u_1 can use the short-cut route with a maintenance of h_{acc} to move from c_1 to c_3 finally.

Secondly, suppose that u_2 operated by t_2 have delivered an ordered item of c_6 and is looking for the short-cut route between c_6 and c_4 as Fig. 2(c). Although c_4 and c_6 have the membership of



(a) Movement scenario 1 (b) Movement scenario 2 (c) Movement scenario 3 (d) Movement scenario 4

Fig. 3. Various movement scenarios of UAVs with an elevation view.

t_2, c_5 is not member of t_2. Thus, c_5 will not allow the penetration of u_2 as access mode of h_{acc}. For this case, u_2 may choose the route from c_6 to c_4 requiring the mode transition between h_{acc} and h_{pre}. That is, before entering into c_5, u_2 increases its altitude to convert h_{acc} into h_{pre}. After passing through c_5 and entering the area of c_4, u_2 also change its mode from h_{pre} to h_{acc} so as to deliver an item to c_4. At this scenario 2 in Fig. 2(c), the item will be carried with more delayed delivery time compared with scenario 1 in Fig. 2(b).

Thirdly, in Fig. 2(d), we have scenario 3 that u_3 controlled by t_3 tries to deliver an item from current location c_4 to c_6. Because c_4 and c_6 are members of t_3, u_3 can trespass on c_4 and c_6 with h_{acc}. But, since c_5 is not a member of t_3, c_5 will not give the permission for the intrusion of u_3 as h_{acc}. Similar to scenario 2, u_3 may use the route from c_4 to c_6 by passing through c_5 with a conversion of mode between h_{acc} into h_{pre}. Otherwise, u_3 may use another path by following public points. It follows that u_3 can use the trajectory with the following visiting order: c_4, p_3, p_2, p_1, c_6 as Fig. 2(d). Note that this trajectory also requires the mode conversion when u_3 enters into p_3 and then it moves from p_1 to c_6, respectively.

D. Applicable Scenarios With an Elevation View

Next, for same scenarios depicted in Section III-C, we provide their elevation views for the application for delivering items using multiple UAVs. Note that we basically have four types of movements of UAVs. The first one is a movement type between permitted neighbor private areas of customers. Second one is a movement between permitted private area and public area. The third one is a movement between private and unpermitted private area. The last one is a movement of UAV between public points.

Remind that there exists a set of U, T within given area A including both the set of private areas C and the set of public points P as it can be seen in Fig. 2(a). Fig. 3 depicts various movement types of UAVs among customers' private areas and public points. Fig. 3(a) shows the movement between permitted private areas of citizens, which is an elevation view of scenario 1 in Fig. 2(b). As shown in Fig. 3(a) for scenario 1, suppose we have three customers c_1, c_2, c_3 (or their private areas) and one UAV u_1 where u_1 is operated by t_1 and it has temporary permissions given by c_1, c_2, c_3. Also, suppose that u_1 has delivered an item to c_1 by dropping it at low altitude as h_{acc} and then tries to deliver items to c_3. Since u_1 can access to c_2's area, u_1 is able to move to c_3 with low altitude without any necessity of increasing altitude u_1 if such a trajectory has shorter distance than a path by public points.

Fig. 3(b) describes another movement type between permitted private area and public point. As scenario 2 in Fig. 3(b), we have u_2 handled by t_2 and the customers c_4, c_5, c_6. After delivering an item at c_6 with h_{acc}, c_6 tries to carry an item to c_4. But, because c_5 does not allow the penetration of u_2 with a low altitude, u_2 rise its height as h_{pre} and then keep its altitude when u_2 passes through c_5. Once u_2 arrives at c_4's area, u_2 decreases its own altitude into h_{acc} to deliver the ordered item by c_4. In scenario 2, there exists vertical movements with a long time delay for transition between h_{acc} and h_{pre}.

Furthermore, for scenario 3 in Fig. 2(d), we provide its elevation views in Fig. 3(c) and 3(d) where Fig. 3(d) represents the expanded view of public points in Fig. 3(c). At scenario 3, we have u_3 which is controlled by t_3 and tries to carry an item from current location c_4 to c_6. Also, c_4 and c_6 are members of t_3 and then it is possible that u_3 is able to access into c_4 and c_6 with h_{acc}. But, since c_5 is not a member of t_3, c_5 will not give the permission for the intrusion of u_3 as h_{acc}. Therefore, if we choose the path including public points, u_3 at c_4 should convert own height from h_{acc} and h_{pre} as shown in Fig. 3(c). Then, with keeping h_{pre}, u_3 passes through public points p_3, p_2, p_1 as Fig. 3(d). Once u_3 arrives c_6's region, it changes own mode from h_{pre} to h_{acc} with a long moving delay. So, u_3 completes the delivery by dropping the ordered item by c_6 at h_{acc}.

IV. A Framework for Differential Privacy Preserving Movements of Multiple UAVs

Now, we introduce a framework to provide privacy preserving movements of multiple UAVs. We first introduce important terms and formally define the problem to be considered in the proposed framework. Then, we represent *UDiPP graph* that is a graph converted from given network information.

A. Privacy Violation of UAV

Since the proposed framework considers preserving citizens' privacy, it is essential to define a detection of privacy violation by UAV. Then, suppose that each customer is located at a center of the virtual square which consists of four corners where a length of line segment of the square is l_{vs}. Also, a sensor with sensing

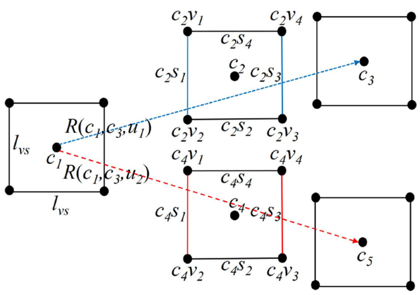


Fig. 4. An example of penetration decision.

range l_{vs} is positioned at each corner of the square and is able to cover the square. So, any penetration by objects into the square is detected by the sensor. Also, assume that each virtual square has an equal size. Then, we formally define privacy violation of UAV as follows.

Definition 4.1 (Privacy violation of UAV): Given a set of customers C and its virtual squares, it is identified as *privacy violation* of UAV if UAV's route between permitted customers is crossing with any line segment of virtual squares of unpermitted customers.

Fig. 4 depicts a case of detecting a privacy violation by UAV. Suppose that we have two UAVs u_1, u_2 and five customers c_1, c_2, c_3, c_4, c_5 that each customer has a virtual square consisting of four corner points and four line segments, which each sensor is located at the corner of the square with a length of line segment l_{vs}. Also, u_1 has access permission for c_1, c_2, c_3 and u_2 can access into c_1, c_5 given by access permission. For instance, as shown in Fig. 4, c_2 has four corner points $c_2v_1, c_2v_2, c_2v_3, c_2v_4$ and four line segments $c_2s_1, c_2s_2, c_2s_3, c_2s_4$. Assume u_1 and u_2 are currently located at c_1 with a preserving mode h_{acc}. And, u_1 tries to move to c_3 and u_2 plans to move to c_5 to deliver their items. Before using public points requiring mode transition from h_{acc} to h_{pre}, u_1 first calculates a straight route $R(c_1, c_3, u_1)$ passing through segments c_2s_1, c_2s_3 of c_2. Since u_1 has a permission of c_2, u_1 can follow the route $R(c_1, c_3, u_1)$ regardless of passing through those segments of c_2. On the other hand, u_2 with h_{acc} at c_1 estimates the straight route $R(c_1, c_5, u_2)$ from c_1 to c_5 before using public points to reach at c_5. As it can be seen in Fig. 4, $R(c_1, c_5, u_2)$ is crossing with segments c_4s_1, c_4s_3. Because u_2 does not have access permission into c_4, the route crossing segment without permission is verified as privacy violation.

B. Problem Definition

We note that the proposed framework carefully handles an issue of differential privacy preserving movement which is defined as follows.

Definition 4.2 (UAVs' differential privacy preserving (UDiPP) movements): Given a set of UAVs U, a set of customers C and a set of public points P within an area A, different access permissions by customers are pre-assigned to U. The *UAVs' differential privacy preserving (UDiPP) movements* are to guarantee that U visit C without any privacy violation.

Based on above Definition 4.2, we formally define our problem as follows.

Definition 4.3 (MintUDiPP problem). Given a set of UAVs U, a set of customers C and a set of public points P within an area A, different access permissions by customers are pre-assigned to U. The *MintUDiPP* problem is to minimize total UAVs' differential privacy preserving movements such that every customer in C is to be visited by U.

Then, we formally present *MintUDiPP* problem using ILP formulation. With notations in Table I, we additionally represent a more detail description for the below integer variables.

$$W_{i,j} = \begin{cases} 1, & \text{if a UAV } u_i \text{ moves to the customer } c_j \\ 0, & \text{otherwise.} \end{cases}$$

$$X_{i,j} = \begin{cases} 1, & \text{if there is no privacy violation by } u_i \\ & \text{when UAV } u_i \text{ moves to the customer } c_j \\ 0, & \text{otherwise.} \end{cases}$$

$$Y_{i,j} = \begin{cases} 1, & \text{if the public path is utilized} \\ & \text{when UAV } u_i \text{ moves to the customer } c_j \\ 0, & \text{otherwise.} \end{cases}$$

$$Z_j = \begin{cases} 1, & \text{if a customer } c_j \text{ is visited} \\ 0, & \text{otherwise.} \end{cases}$$

Then, *MintUDiPP* problem can be formulated as follows.

$$\textbf{Minimize} \sum_{i=1}^{k} \sum_{j=1}^{n} (\mu_{i,j} \cdot W_{i,j} \cdot X_{i,j}) + (\mu_{i,j} \cdot W_{i,j} \cdot Y_{i,j}) \tag{1}$$

Subject to:

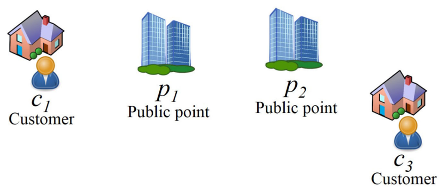
$$\sum_{i=1}^{k} W_{i,j} \leq 1, (\forall j) \tag{2}$$

$$\sum_{i=1}^{k} X_{i,j} + Y_{i,j} = 1, (\forall j) \tag{3}$$

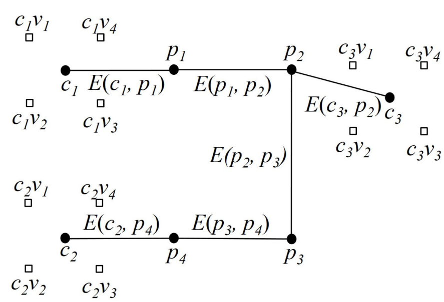
$$\sum_{j=1}^{n} Z_j = n \tag{4}$$

From (1), our objective function is to minimize total moving distance between the initial locations of UAVs and the customers such that every customer is visited by UAVs using UAVs' differential privacy preserving movements where $\mu_{i,j}$ is a distance including privacy preserving movement and public path when u_i moves to c_j. Also, constraint (2) requires that each customer c_j can be visited by UAV u_i at most once. By constraint (3), it is satisfied that the customer c_j can be visited by UAV u_i through the trajectory without privacy violation or the public path. Finally, constraint (4) guarantees that the total number of visited customers is n.

Also, it is noted that there will be infinite number of points within a public area, which UAVs can use as continuous paths. To reduce the complexity of deciding or finding points within



(a) Given UAV networks environment



(b) Conversion into UDiPP graph

Fig. 5. An example of conversion from given network environment into UDiPP graph.

Algorithm 1: UDiPP-Graph-Creation.

Inputs: A, C, P, Output: $\mathcal{G} = (V, E, S)$

set $V = \emptyset$;
set $E = \emptyset$;
set $S = \emptyset$;
verify C, P in A;
$V \leftarrow (C \cup P)$;
if there exists an edge between p_i and p_j where $p_i, p_j \in P, \forall i$ **then**
  $E \leftarrow E(p_i, p_j)$;
end if
search for the closest public point p_j for each customer c_i, where $c_i \in C, p_j \in P$ for $\forall i$;
if an edge is found between a customer and its closest public point p_j where $c_i \in C, p_j \in P$ for $\forall i$ **then**
  $E \leftarrow E(c_i, p_j)$;
end if
generate four corner points $c_i v_j$ of virtual square s_i for each customer c_i, where $EucDist(c_i, c_i v_j) = r$, $c_i \in C, v_j \in \{v_1, v_2, v_3, v_4\}$ for $\forall i, j$;
if it is created **then**
  $s_i \leftarrow c_i v_j$;
  $S \leftarrow s_i$
end if
return $\mathcal{G} = (V, E, S)$

the public area, we consider a finite set of public points as potential positions or waypoints of UAVs. So, for the solution to be feasible, we generate a finite set of public points within the public area so that it is guaranteed that the solution of *MintUDiPP* problem exists in the set of public points such that UAVs fly over those public points with the high altitude of preserving mode.

C. UDiPP Graph

In the proposed framework, we create *UDiPP graph* which is based on system information including customers, UAVs, public points. So, it is possible that using those given system information, it is converted into *UDiPP graph* which consists of the set of vertices, edges, virtual squares.

Then, *UDiPP graph* is formally defined as follows.

Definition 4.4 (UDiPP graph). Given information for C, U, P, *UDiPP graph*, $\mathcal{G} = (V, E, S)$, is a graph which is composed of the set of vertices, edges, virtual squares.

Fig. 5 represents an example of conversion from given network environments into *UDiPP graph*. Fig. 5(a) depicts given network status. It includes three customers c_1, c_2, c_3 and four public points p_1, p_2, p_3, p_4 within area A. Suppose that a customer is connected with the closest public point. On the other hand, Fig. 5(b) shows the converted status from given environment into *UDiPP graph* $\mathcal{G} = (V, E, S)$. All customers and public points are converted as vertices. So, seven vertices in Fig. 5(b) are included at a set of vertices, V. For a set of edges E, an edge is created between public points as well as a customer and the closest public of the customer. So, the edges $E(c_1, p_1), E(c_2, p_4), E(c_3, p_2), E(p_1, p_2), E(p_2, p_3), E(p_3, p_4)$ are included at a set of edges E. Also, we consider the virtual squares of each customer. So, each customer creates four corner points and they are covered by a set of virtual square, S. In Fig. 5(b), sixteen corner points are included at S.

V. The Proposed Approaches

In this section, we develop three algorithms: The first algorithm is for creation of *UDiPP graph*. The second algorithm is to detect privacy violation of UAVs. Based on these algorithms, the third algorithm is proposed to solve the *MintUDiPP* problem. Those algorithms are detailed as follows.

A. Creation of UDiPP Graph

To generate *UDiPP graph*, we first implement *UDiPP-graph-creation* which basically performs the below steps.

- Identify C, P in A and add them to a set of vertices, V in $\mathcal{G}$.
- For public points, if there exists an edge between public points, then we add it to a set of edges, E in $\mathcal{G}$.
- For every customer, if there exists an edge between a customer and the closest public point, then add it to a set of edges, E in $\mathcal{G}$.
- Also, for every customer, create four corner points of the virtual square and then add to a set of virtual squares, S in $\mathcal{G}$.

The pseudocode of *UDiPP-graph-creation* is represented in Algorithm 1.

Algorithm 2: Privacy-Violation-Detection.

Inputs: $\mathcal{G} = (V, E, S), a, b, t_i$, Output: D_{ind}
set $C_{\neg t_i} = \emptyset$;
set $D_{ind} = false$;
while $j <= n$ **do**
  from C with size n, identify every customer c_j who do not allow t_i;
  if there exists **then**
    $C_{\neg t_i} \leftarrow c_j$;
  end if
end while
from $\mathcal{G} = (V, E, S)$, identify virtual squares of customers in $C_{\neg t_i}$;
from $\mathcal{G} = (V, E, S)$, identify four corner points of each virtual square, $c_j v_1, c_j v_2, c_j v_3, c_j v_4$, where $c_j \in C_{\neg t_i}$;
draw four line segments $\overline{(c_j v_1, c_j v_2)}, \overline{(c_j v_2, c_j v_3)}, \overline{(c_j v_3, c_j v_4)}, \overline{(c_j v_4, c_j v_1)}$ for each virtual square;
draw a virtual straight line $\overline{(a, b)}$ between a and b where $a, b \in \{C\}$;
check if $\overline{(a, b)}$ is crossing with any segments of each virtual square;
if there exists **then**
  $D_{ind} = true$;
end if
return D_{ind}

Algorithm 3: UDiPP-movement.

Inputs: $\mathcal{G} = (V, E, S), A, U, C, S, P, T, n, m, U_{loc}, d_{pub}, d_{mod}$,
Output: U_{tmd}
set $U_{tmd} = 0$;
set $C' \leftarrow C$;
while $C' \neq \emptyset$ **do**
  search for pairs without privacy violation by calling Algorithm 2 for every pair between c_i and UAV u_j, where $c_i \in C, u_j \in U_{loc}$;
  if there exist **then**
    choose a pair (c_i', u_j') with the shortest distance from those pairs;
    $U_{tmd} = U_{tmd} + EucDist(c_i', u_j')$;
    $C' \leftarrow C' - c_i'$;
    update U_{loc};
  else
    find a pair with the shortest distance through public points for every pair between c_i and UAV u_j, where $c_i \in C, u_j \in U_{loc}$;
    calculate the distance of the found pair and update it as d_{pub};
    $U_{tmd} = U_{tmd} + d_{pub}$;
    calculate the distance for mode transition d_{mod};
    $U_{tmd} = U_{tmd} + 2 \cdot d_{mod}$;
    $C' \leftarrow C' - c_i'$;
    update U_{loc};
  end if
end while
return U_{tmd}

B. Detection of Privacy Violation

To detect privacy violation by UAVs, we develop *privacy-violation-detection* algorithm between given two entities. The steps can be summarized as follows.

- Draw a virtual straight line between two target points, a and b, where $a, b \in \{C\}$.
- Find all customers who do not allow the UAV for two target customers.
- Check if the virtual straight line is crossing with any segments of the found customers' virtual squares.
- If there exists, the UAV violates a privacy of the customers. So, return D_{ind} as $true$. Otherwise, return D_{ind} as $false$.

The pseudocode of *privacy-violation-detection* is presented in Algorithm 2.

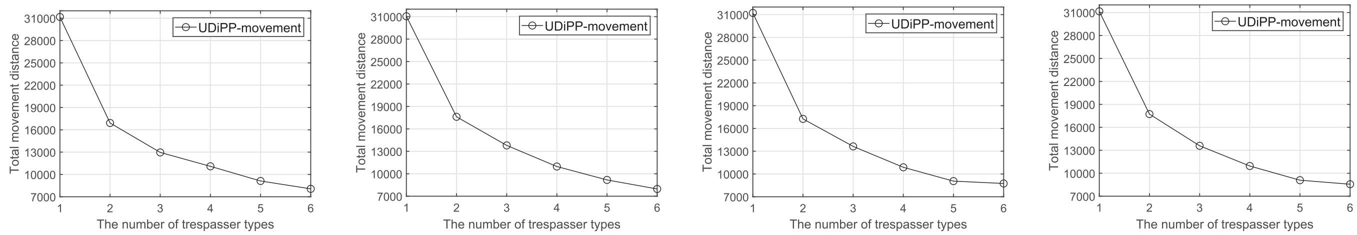
C. The Proposed Approach for UDiPP Movement

In order to solve *MintUDiPP* problem, we propose an approach, which is called as *UDiPP-movement*. Then, the *UDiPP-movement* is performed by the below procedures.

- Verify the set of UAVs and the customers to be visited.
- We implement the below steps.
  - Search for all pairs without privacy violation between current UAVs and customers to be visited and by calling Algorithm 2 *privacy-violation-detection*.
  - If we have pairs without privacy violation, then choose a pair with the shortest distance and add the distance to a total distance of UAVs, U_{tmd}. Also, update U_{loc} for the selected pair.
  - If current UAV can not support privacy-preserving movement, then use the closest public point and follow public points to reach any customer to be visited. Because there exist the UAV mode transitions between h_{acc} and h_{pre}, add both the distance d_{mod} of those transitions and the distance among public points d_{pub} to U_{tmd}. Also, update U_{loc} for the current UAV.
- If the scheduled every customer is visited by UAVs, return U_{tmd}.

The above steps are iterated until the scheduled customers are visited by UAVs. The pseudocode of *UDiPP-movement* is described in Algorithm 3.

In summary, Algorithm 1 generates *UDiPP graph* with the input C, P, A. Then, it returns *UDiPP graph*: $\mathcal{G} = (V, E, S)$ as the output. Also, Algorithm 2 is for detecting if there exists a privacy violation by UAV with the input $\mathcal{G} = (V, E, S), a, b, t_i$. It returns D_{ind} as $true$ if there exists privacy violation where the virtual straight line between a and b is crossing with the virtual square segments of the customers who do not allow the UAV. Otherwise, it returns D_{ind} as $false$. Based on the Algorithm 1 and Algorithm 2, the Algorithm 3 calculates the possible minimum total movement distance U_{tmd} without privacy violation by UAVs.



(a) The number of UAVs = 9 (b) The number of UAVs = 11 (c) The number of UAVs = 13 (d) The number of UAVs = 15

Fig. 6. Total movement distance by *UDiPP-movement* for different number of trespasser types with various number of UAVs.

VI. Evaluation and Performance Analysis

A. Experimental Evaluation

In this section, we analyze the performance of the proposed scheme *UDiPP-movement* by various scenarios. Using ad-hoc simulator and the source code with C^{++} language, the experiments have been implemented by the server that has Intel Core i7-2600 CPU, CPU op-mode with 32 bit and 64-bit, L1d cache with 32K and L1i cache with 32K, L2 cache with 256K, L3 cache with 8192K.

Based on those settings, we considered three different groups of simulations through several ROIs such as width 500 meter $\times$ height 500 meter, 500 $\times$ 600, 500 $\times$ 700, 500 $\times$ 800, 500 $\times$ 900. The number of customers n ranges from 30 to 80 and the number of UAVs k is ranging from 5 to 15 and then the number of trespasser types m ranges from 1 to 4 where each UAV may have multiple trespasser types in our simulations. Also, we used the following parameter settings that the number of public q is 100, the distance d_{pub} between public points is 10 meter, the distance d_{mod} between access mode and preserving mode of UAV is 100 meter and the line length of virtual square l_{vs} is 5 meter. Note that each simulation in the result graphs represents the average value of 50 different graph sets for total movement U_{tmd}.

In the first group of experiments, the proposed approach *UDiPP-movement* has been performed to evaluate the total movement distance U_{tmd} for different number of trespasser types m from 1 to 6 with various number of UAVs k from 9 to 15 in the area of 500 $\times$ 500. The first group of simulations uses the setting that the number of customers n is 50, the number of public q is 100, the distance d_{pub} between public points is 10 meter, the distance d_{mod} of UAV mode transition is 100 meter and l_{vs} is 5 meter. Fig. 6(a) and Fig. 6(b) show the total moving distance U_{tmd} with the number of UAVs k is 9 and 11, respectively. Also, Fig. 6(c) and Fig. 6(d) present the result with k is 13 and 15. As it can be seen from Fig. 6 as a whole, the total movement distance U_{tmd} decreases as the number of trespasser types increase. The reason is that given k, UAVs may have more movement flexibility from current locations to next customers to be visited when UAVs are included in more number of trespasser types m. Therefore, in Fig. 6, we can check that U_{tmd} is returned with the smallest value when m has the biggest value 6 in the experiment.

For the second group of simulations, we executed *UDiPP-movement* to get U_{tmd} for different number of customers n ranging from 30 to 80 with various number of UAVs k from 5 to 11 in the area of 500 $\times$ 500. We have utilized the setting that m is 3, q is 100, d_{pub} is 10, d_{mod} is 100, l_{vs} is 5. Fig. 7(a) and Fig. 7(b) represent U_{tmd} with the number of UAVs k is 5 and 7. Also, Fig. 7(c) and Fig. 7(d) show U_{tmd} when k is 9 and 11. As we can see the result in Fig. 7, the total movement distance U_{tmd} increases as the number of customers increases given k because the given number of UAVs basically should visit more number of customers so that *UDiPP-movement* returns bigger value of moving distance of UAVs.

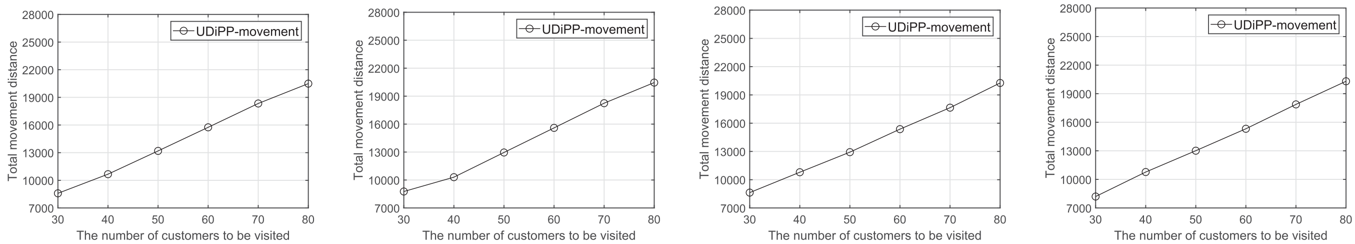
Finally, the third group of experiments focuses on the performance evaluation with different sizes of square-shaped ROI with 500 $\times$ 600, 500 $\times$ 700, 500 $\times$ 800, 500 $\times$ 900, respectively. The setting in the third group experiment is equal to the second group. Fig. 8(a) and Fig. 8(b) display U_{tmd} where the size of ROI is 500 $\times$ 600 and 500 $\times$ 700. In addition, Fig. 8(c) and Fig. 8(d) show the result of U_{tmd} when the size of ROI is 500 $\times$ 800 and 500 $\times$ 900. Similar to the result of second group experiment, the total movement distance U_{tmd} increases as the number of customers n increases with given number of UAVs k. We verify the performance result of *UDiPP-movement* for different sizes of ROI from Fig. 8.

B. Complexity Analysis of the Proposed Algorithms

In this section, we analyze the complexity of the proposed Algorithm 1, 2, 3. Suppose that the total number of UAVs is k, the total number of customers to be visited is n and the total number of public points is q where $n > k$ and $n > q$.

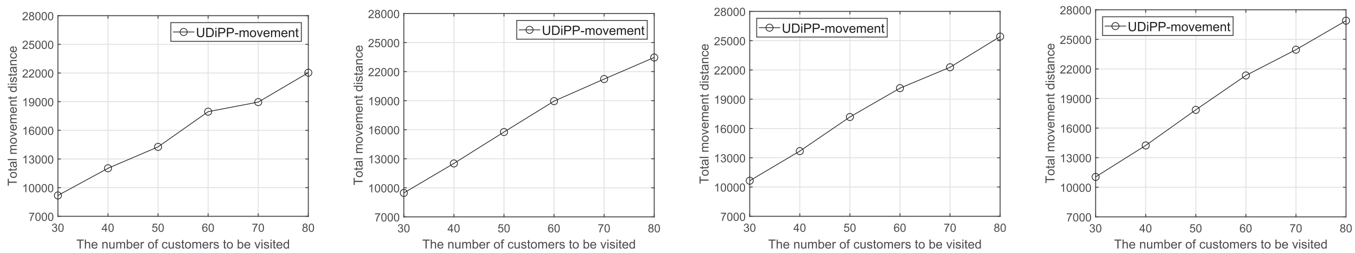
First, if we consider the complexity of Algorithm 1, it performs iterations to check if there is an edge between the public points and then, the number of the iterations is q^2. Also, Algorithm 1 generates an edge between each customer and the closest public point so that it has the maximum number of iterations as $q * n$. Then, Algorithm 1 creates four corner points for each customer. It follows that the number of iterations for the generation of corner points is $4 * n$. If so, the total number of iterations will be $q^2 + (q * n) + (4 * n)$. Since q^2, q and 4 are constants, the asymptotic upper bound is $O(n)$. So, the complexity of Algorithm 1 is considered as $O(n)$.

Secondly, if we derive the complexity of Algorithm 2, it first draws a virtual line between the target points a and b, which requires $O(1)$. Also, Algorithm 2 implements iterations to identify every customer who does not allow t_i between a and b. Then, the number of iterations is n. After the verifying four corner points of each virtual square with $4 * n$, Algorithm 2 verifies if the virtual straight line between a and b is crossing with any segments of each virtual square. Then, it will require



(a) The number of UAVs = 5 (b) The number of UAVs = 7 (c) The number of UAVs = 9 (d) The number of UAVs = 11

Fig. 7. Total movement distance by *UDiPP-movement* with different number of customers with various number of UAVs.



(a) Width 500 × height 600 (b) Width 500 × height 700 (c) Width 500 × height 800 (d) Width 500 × height 900

Fig. 8. Total movement distance by *UDiPP-movement* with different number of customers with various width and height sizes of ROI.

the maximum number of iterations as $4 * n$. If so, the total number of iterations is $n + (4 * n) + (4 * n) + 1$. Since 4 and 1 are constants, the asymptotic upper bound is $O(n)$. So, the complexity of Algorithm 2 is considered as $O(n)$.

Lastly, if we estimate the complexity of Algorithm 3, it looks for pairs without privacy violation by calling Algorithm 2 with the target c_i and UAV u_j that has the total number of iterations is be $n + (4 * n) + (4 * n) + 1$. If it is found where the found number of pairs is z, we select the pair with the shortest distance from the founded pairs. Then, it requires the maximum number of iterations as z. Besides, If it is not found, Algorithm 3 searches for a pair with the shortest distance through public path consisting of public points and UAV. It will require the maximum number of iterations as $q * k * n$. Then, calculate the distance of the found pair and the distance for mode transition which is estimated as $O(1)$ and $O(1)$, respectively. Based on the above part, the total number of iterations will be as follows. $n + (4 * n) + (4 * n) + 1 + (q * k * n) + 1 + 1 = (qk + 9)n + 3$. Since q and k are constants, the asymptotic upper bound is $O(n)$. Hence, as asymptotic upper bound as the worst case, the complexity of Algorithm 3 is considered as $O(n)$.

VII. Conclusion

The use of multiple UAVs gives clear advantages to numerous applications. However, such a proliferation of UAVs in urban environment will bring about critical issues such as privacy. In this paper, we introduced a new framework to support privacy preserving movement with a consideration of differential permissions for multiple UAVs in smart cities. Also, after the generation of *UDiPP graph* with given components, we formally defined *MintUDiPP* problem whose objective is to minimize total movement with differential permissions based on the graph model. To solve the problem, a novel approach *UDiPP-movement* is proposed as well as is performed by extensive experiments with various scenarios and then analyzed the performance of the proposed scheme.

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