DETERMINATION OF MINIMUM NUMBER OF UAVS FOR LOCAL AREA NETWORKS OF DRONES

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ABSTRACT

There are many applications of Unmanned Aerial Vehicle (UAV) networks where all UAVs belong to one organization or a person. In such applications, the number of UAVs that can be employed is limited due to the cost factor. Local Area Networks of Drones (LoDs) have been introduced recently for such purposes. This paper presents methods of determining the minimum number of UAVs to perform tasks in four basic categories of LoD applications: completing a single task at a time, completing multiple tasks simultaneously, monitoring the entire area using a single UAV branch and monitoring the entire area simultaneously using multiple branches of UAVs. Completing one task at a time always requires a minimum number of UAVs and increasing the number of simultaneous tasks performed always increases the number of UAVs required for any application.

KEYWORDS

LoDs, UAV Networks, Minimum number of Drones

1. INTRODUCTION

When first introduced, Unmanned Aerial Vehicles (UAVs), commonly known as drones, were solely used for military applications [1], but with the advancements of UAV technology, small UAVs has now gained enormous popularity in civil and commercial applications [2]. As a recent advancement, various research groups have started designing UAV networks, because of their increased efficiency and capabilities compared to individual UAVs. A LoD is such a UAV network type, which is suitable for individuals or organizations to be used in certain applications. In contrast to Local Area UAV networks, a LoD minimizes the total number of UAVs required to perform a given task due to its star-connected relay topology [3]. Star-connected relay topology is a network topology where groups of UAV nodes are connected at tandem in rows, and the last UAV nodes at one end of each row are connected to a head end controller, which is the Ground Station (GS). The UAV nodes connected in tandem are called the branches of the network. The GS can be placed in an easily accessible location, and the UAV branches can reach any given target location to perform a given task, while maintaining communication with the GS via the branch itself.

The minimum number of UAVs required for a given application is one of the main factors which govern the economic feasibility of a LoD. For a commercial application such as agriculture, the economic feasibility of a LoD is a critical factor in decision making. In certain applications such as natural disaster monitoring or national security surveillance, the economic factor is not as critical as in commercial applications. However, due to the nature of these emergency service applications, the resources should be immediately available upon request. In other words, the LoDs should be deployed for missions with a sufficient number of UAVs at short notice. Therefore, users should be aware of the minimum number of UAVs required to perform a given

task. In this paper we discuss the methods of determining the minimum number of UAVs for a given LoD application. These methods will help improve the practical applicability of LoD networks.

The rest of the paper is organized as follows. In Section 2 we discuss a few literature related to UAV network types and few publications on LoDs. In Section 3, we discuss the methods of determining the minimum number of UAVs in different categories of UAV applications. This section further includes the simulation results of the discussed methods. Finally, we conclude the paper in Section 4.

2. BACKGROUND

In this section, we first discuss previously published work on various UAV network types and UAV network topologies. Then, we present recent findings of research publications on LoDs.

Flying Ad hoc Networks (FANETs) [4] have been proposed in the literature as a type of UAV network. A FANET is fundamentally an ad hoc network of UAV nodes. The concept of a FANET is based on a Vehicular Ad hoc Network (VANET) [5]. VANET was developed to maintain an ad hoc network of ground vehicles [6]. In order to transfer messages between UAV nodes and the GS in both directions, there should be communication paths in a UAV network. Routing protocols help determine the communication paths in UAV networks. A routing protocol consists of an algorithm to determine the optimal communication path between a source node and a destination node under a certain performance criterion. Many research articles have been published on routing protocols of FANETs [7-9]; however, an underlying assumption in all these routing protocols is that there is at least one UAV neighbor node for a UAV node that has a message to route, requiring many UAVs in a FANET.

Another UAV network type that has been introduced recently is the Internet of Drones (IoD) [10]. IoD is a cellular network infrastructure of UAV nodes. In this network, the total geographical area is divided into several zones, and each zone consists of a GS. Any UAV node flying over a zone directly connects to the GS of that specific zone, and all GSs are connected together to form a single network. However, placing GSs to cover the whole operating environment is not feasible in certain applications. For instance, in bush fire monitoring applications it is not possible to place GSs in an operating environment. Also, there is a great chance of network infrastructure being destroyed by the propagating fire. Additionally, profit-driven application areas, such as agriculture and parcel delivery, do not encourage the use of multiple GSs due to the cost.

The network topology of a communication network specifies the layout of networks nodes and the paths of information flow through the network. The topology of a UAV network is a critical factor as it has an impact on the number of UAV nodes required in the network and the range of mobility of the UAVs within the network.

Frew and Brown [11] recognize that UAV networks can be configured in four basic topologies: direct, satellite, cellular and mesh. In direct network topology, each UAV node connects to the GS via a direct connection. This configuration is not commonly used because the maximum span of the network is the maximum radio distance from the GS to the UAV nodes. In satellite network topology, all UAV nodes connect to a satellite, but this has the disadvantage that every message has to be sent through the satellite, increasing the delay in transmission. In cellular network topology, groups of UAV nodes are connected to multiple base stations, and these base stations connect to the GS. This is the topology that is used in IoDs, and it is more suitable for a public UAV network such as the cellular mobile wireless network. In mesh network topology,

UAV nodes have communication links with their neighbour UAVs. In this topology, UAVs that are not capable of creating a direct connection to the GS, create a connection through other UAV nodes that act as relay UAV nodes [11]. FANETs use this network topology as it has ad hoc nodes belonging to different users. However, one of the disadvantages of FANETs is their lack of security, as the messages have to pass through the UAV nodes belonging to other users. A second, but not very apparent problem with FANETs is the need to have a large number of UAV nodes as neighbour nodes to create links. Recently introduced LoDs have the star-connected relay topology. As LoDs have a limited number of UAVs belonging to the same user, a different topology may result when minimizing the number of UAVs. As such, it can be seen that selecting an appropriate topology for a UAV network depends on the application scenario and the available resources.

FANET and IoD have been developed for applications where a large number of UAV nodes are used, and they are not suitable for application scenarios where a relatively small number of UAVs can be employed. The outcome of this research will support and encourage the usage of LoDs with a minimum number of UAV nodes in such applications by providing optimal UAV node placement.

A LoD enjoys higher network security compared to a FANET or an IoD, because in the latter, the network is shared by UAV nodes that belong to different users. As mentioned in the introduction, a LoD requires the least number of UAVs to perform a given task due to its star connected relay topology. Recent research has presented methods of determining desired trajectories of all UAVs in a LoD in order to minimize time or energy consumed to perform a given target [12]. These research publications also discuss the methods of determining desired UAV trajectories in real-world applications by avoiding obstacles. Another paper presents a method of determining the minimum number of UAV branches required for a LoD to achieve a specified level of reliability[13]. However, there are no publications that specifically discuss the methods of determining the minimum number of UAVs in a LoD to perform a given task.

3. DETERMINATION OF MINIMUM NUMBER OF UAVS

The minimum number of UAVs required for an application depends on two main factors; the geometric shape and dimensions of the land and the number of tasks performed simultaneously. Intuitively, the geometric dimensions of the operating land have a direct effect on the minimum number of UAVs required. The larger the land, the higher the number of UAVs required to reach all locations on the land from the GS. Additionally, if there are two pieces of land with exactly the same surface area, but with two different shapes, the minimum number of UAVs required to perform tasks in these two lands are not necessarily equal.

A LoD which performs multiple tasks simultaneously requires more UAVs compared to a LoD which only performs a single task at a time. For instance, assume the leading UAV of a LoD branch is performing a task at one location, and GS needs to send another UAV to a distinct second location. Then the LoD should be able to send another leading UAV to the second location without losing communication to its first leading UAV. Therefore, if the user intends to perform multiple tasks at the same time, then the LoD should have enough UAVs to deploy to multiple targets when necessary. Dispatching UAVs to multiple targets simultaneously is discussed thoroughly later in this chapter.

We can subdivide the tasks performed by LoDs into four basic categories. Table 1 shows the four categories and examples of their applications. The minimum number of UAVs required to perform in each task category is discussed in the following subsections.

Table 1: Task categorization of LoDs

Task category	Example application
Completing single task at a time	A LoD deployed for an industrial asset monitoring task can monitor assets (e.g., oil rigs, storage tanks, wind turbines) distributed over a vast area sequentially one by one.
Completing multiple tasks simultaneously	A LoD deployed to monitor a bushfire should be able to get footages of bushfire, which escalates in various directions. Therefore, the LoD should be able to send multiple leading UAVs to monitor bushfire in various locations as required.
Monitoring/scanning the entire area using a single UAV branch	A single LoD branch deployed for a land survey can scan across the whole land while each UAV node performs surveying tasks.
Monitoring/scanning the entire area simultaneously using multiple branches of UAVs	A LoD deployed for a criminal incident monitoring task should simultaneously monitor the whole area to assist following and arresting the suspects. Depending on the size and shape of the subjected area, the LoD should have multiple UAV branches to cover the entire area.

3.1. Completing Single Task at a Time

This is the simplest form of tasks, which can be accomplished by a LoD. As mentioned in Table 1, consider an industrial area with large storage tanks and pipelines. Due to safety regulations, these types of assets should be regularly checked and maintained up to the standards. UAVs can easily reach these sorts of assets and provide video and any other sensory data to inspection personnel. A single LoD branch can monitor all the assets sequentially one after the other.
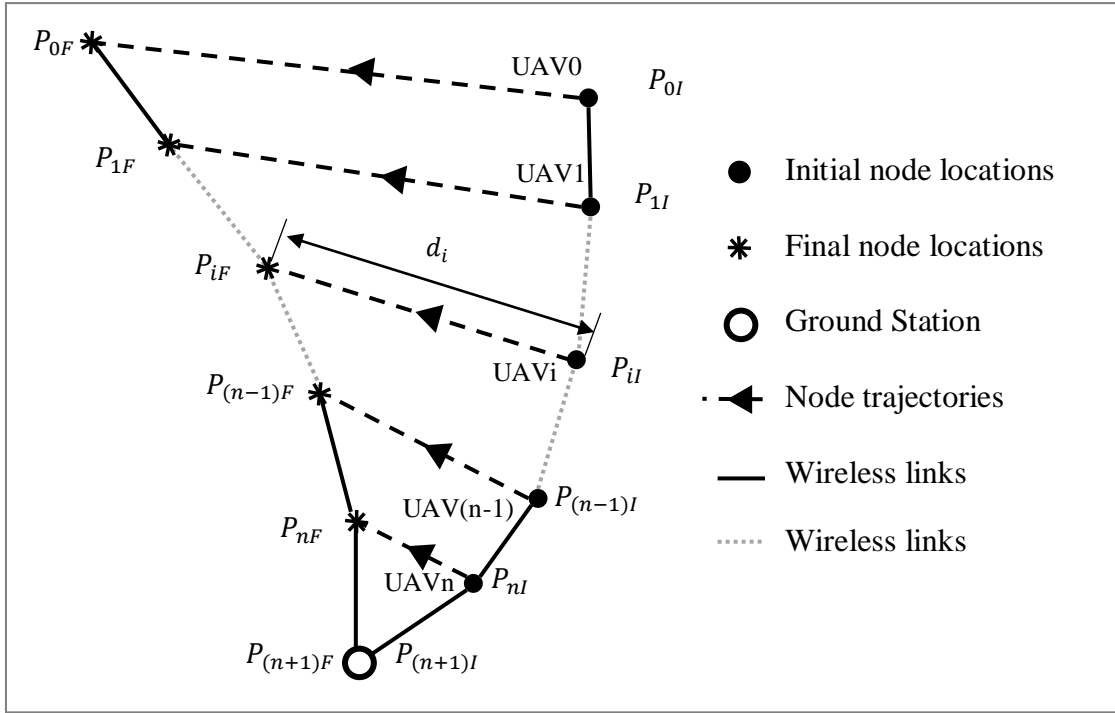
Figure 1: Initial and final locations of UAV nodes

Consider a LoD with a single UAV branch and $n + 1$ number of UAV nodes (Figure 1). As shown in the figure, the nodes are numbered from $i = 0, 1, 2, \ldots, n + 1$ starting from the farthest UAV node to the GS. Note that the last UAV node will be n and the GS will be $n + 1$.

Assume that the leading UAV of the branch moves from its initial location to a given target location. As a result, the ith node moves from its initial location of $P_{iI}(x_{iI}, y_{iI}, z_{iI})$ to the final location of $P_{iF}(x_{iF}, y_{iF}, z_{iF})$. Let X_{iI} and X_{iF} be position vectors in Cartesian coordinates P_{iI} and P_{iF}.

As discussed in Section 2, previous studies have found methods of determining the final UAV node locations of a LoD, while minimizing two parameters, total energy consumption and task completion time. These solutions do not necessarily minimize the number of UAVs utilized. The minimum number of UAVs required in tasks similar to that shown in Figure 1 is found when the final locations of UAVs in the LoD branch lie on the straight line connecting the final target location and the ground station. Therefore, finding the minimum number of UAVs for this sort of task is straightforward. The minimum number of UAVs required can be determined by dividing the distance from GS to the target by the wireless communication range of a single UAV node.

3.2. Completing Multiple Tasks Simultaneously

A single LoD branch is sufficient for any application where tasks are performed one after the other, but if the user needs to keep monitoring one location and dispatch another UAV to a second location, then the GS should be able to send a second LoD branch to the second location or create a sub-branch out of the main LoD branch to reach the next given target. Out of these options, the user can select whichever method requires the least number of UAVs.

Let us consider a piece of land with two distinct targets: Target 1 and Target 2. The leading UAV of a LoD branch of $n + 1$ nodes has already reached Target 1 (Figure 2). The task of the LoD is to send a second leading UAV to Target 2 using a minimum number of UAVs. Note that for visual clarity, Figure 2 only illustrates the leading UAV's locations.
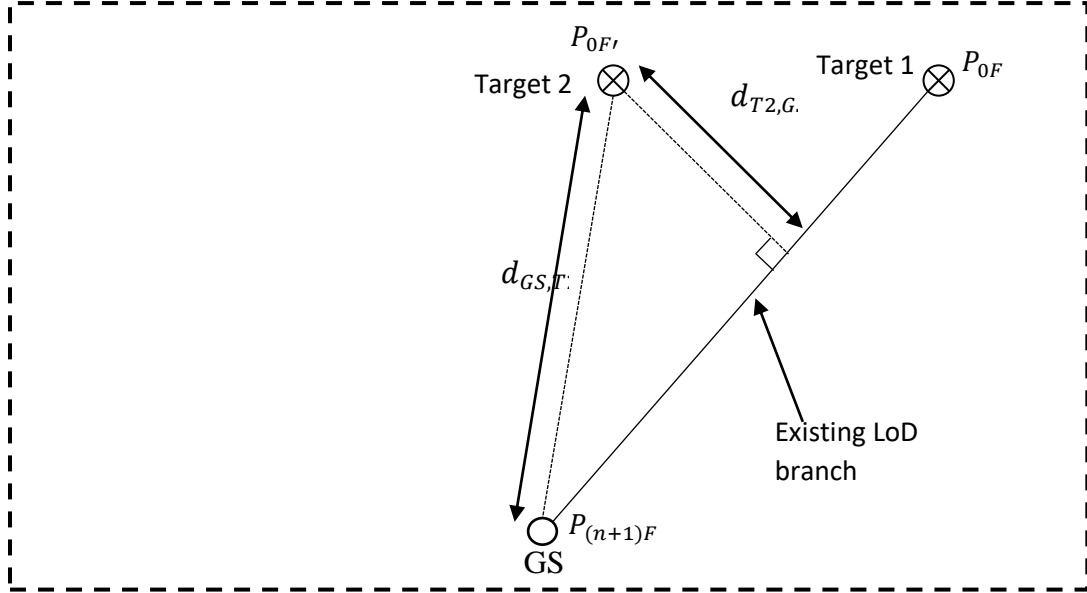

Figure 2. Locations of GS, targets and existing LoD branch

Let us denote Target 1 coordinates and GS coordinates by P_{0F} and $P_{(n+1)F}$, respectively. In addition, let $P_{0F'}$ be the coordinates of the final location of the second leading UAV node.
Distance between GS and Target 2 is given by

$$d_{GS,T2}\big(X_{0F'}, X_{(n+1)F}\big) = \sqrt{\left[\big(X_{0F'} - X_{(n+1)F}\big)\big(X_{0F'} - X_{(n+1)F}\big)^T\right]} \tag{1}$$

Perpendicular distance from Target 2 to the existing LoD branch is given by

$$d_{T2,GST1}\big(X_{0F}, X_{0F'}, X_{(n+1)F}\big) = \frac{\big\|\langle X_{0F} - X_{(n+1)F}\rangle \times \langle X_{0F'} - X_{(n+1)F}\rangle\big\|}{\big\|\langle X_{0F} - X_{(n+1)F}\rangle\big\|} \tag{2}$$

If the perpendicular distance from the Target 2 to the existing LoD branch is less than the distance between Target 2 and the GS, then it requires a fewer number of UAVs to create a sub-branch from the main branch to reach Target 2 than creating a whole new second branch from the GS. Therefore, if the GS location and the target location satisfy the following inequality, the LoD should create a sub-branch to minimize the number of UAVs used to perform the new task while performing the old task.

$$d_{GS,T2} > d_{T2,GST1} \tag{3}$$

Using (1), (2)and (3),

$$\sqrt{\left[\big(X_{0F'} - X_{(n+1)F}\big)\big(X_{0F'} - X_{(n+1)F}\big)^T\right]} > \frac{\big\|\langle X_{0F} - X_{(n+1)F}\rangle \times \langle X_{0F'} - X_{(n+1)F}\rangle\big\|}{\big\|\langle X_{0F} - X_{(n+1)F}\rangle\big\|} \tag{4}$$

Let us further investigate the branch sub-dividing scenario. A sub-branch is created perpendicular to the main branch to minimize the number of UAVs utilized to create a sub-branch. Equation (2) gives the perpendicular distance from the second target to the existing LoD branch. The number of additional UAVs required to create the sub-branch can be calculated by dividing this distance by the wireless communication range. At this point, we have assumed that there is a UAV at the exact location where the sub-branch connects to the main branch (the theoretical sub-dividing point). However, as there could not be a UAV located exactly at the theoretical sub-dividing point, the sub-branch should connect to the closest UAV node located at the GS side of the theoretical sub-dividing point (Figure 3). If the distance to the closest UAV node on the GS side is greater than the wireless communication range, the closest UAV node on the GS side should move along the branch until it enters the wireless communication range of the sub-branch. This new location becomes the actual sub-dividing point of the sub-branch.
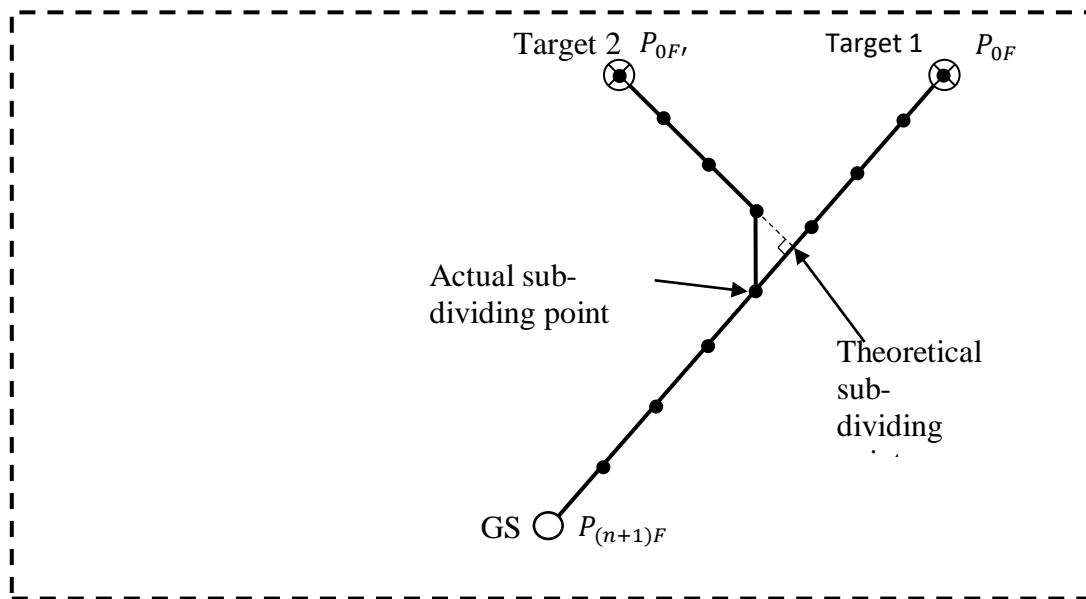

Figure 3. A LoD reaching two targets to perform two tasks simultaneously

Let us further elaborate the above scenario using the following simulation.

Simulation 1: Consider a rectangular field (Figure 4) specified by coordinates (0, 0), (1000, 0), (0, 500) and (1000, 500) in meters. The GS was located at coordinates (500, 20), and the LoD branch consisted of five UAV nodes. The leading UAV was at Target 1 given by coordinates (300, 400) and Target 2 was located at coordinates (600, 400). A MATLAB plot was generated to graphically represent the rectangular field, UAV locations, GS location and the target locations. The LoD had two options to create the second branch to Target 2 location; creating a new LoD branch starting from GS and creating a sub-branch from the main LoD branch. MATLAB programming tools were then used to solve equations (1) and (2) to derive UAV branch lengths and the number of additional UAVs required to reach Target 2 in both options. Figure 4 (a) shows that a UAV of LoD could reach Target 2 by creating a new LoD branch starting from GS containing four UAV nodes. Figure 4 (b) shows that a UAV of LoD could also reach Target 2 by creating a sub-branch of three UAV nodes from the main LoD branch. For this specific scenario, creating a sub-branch from the main branch needed fewer number of UAVs compared to creating a new branch.
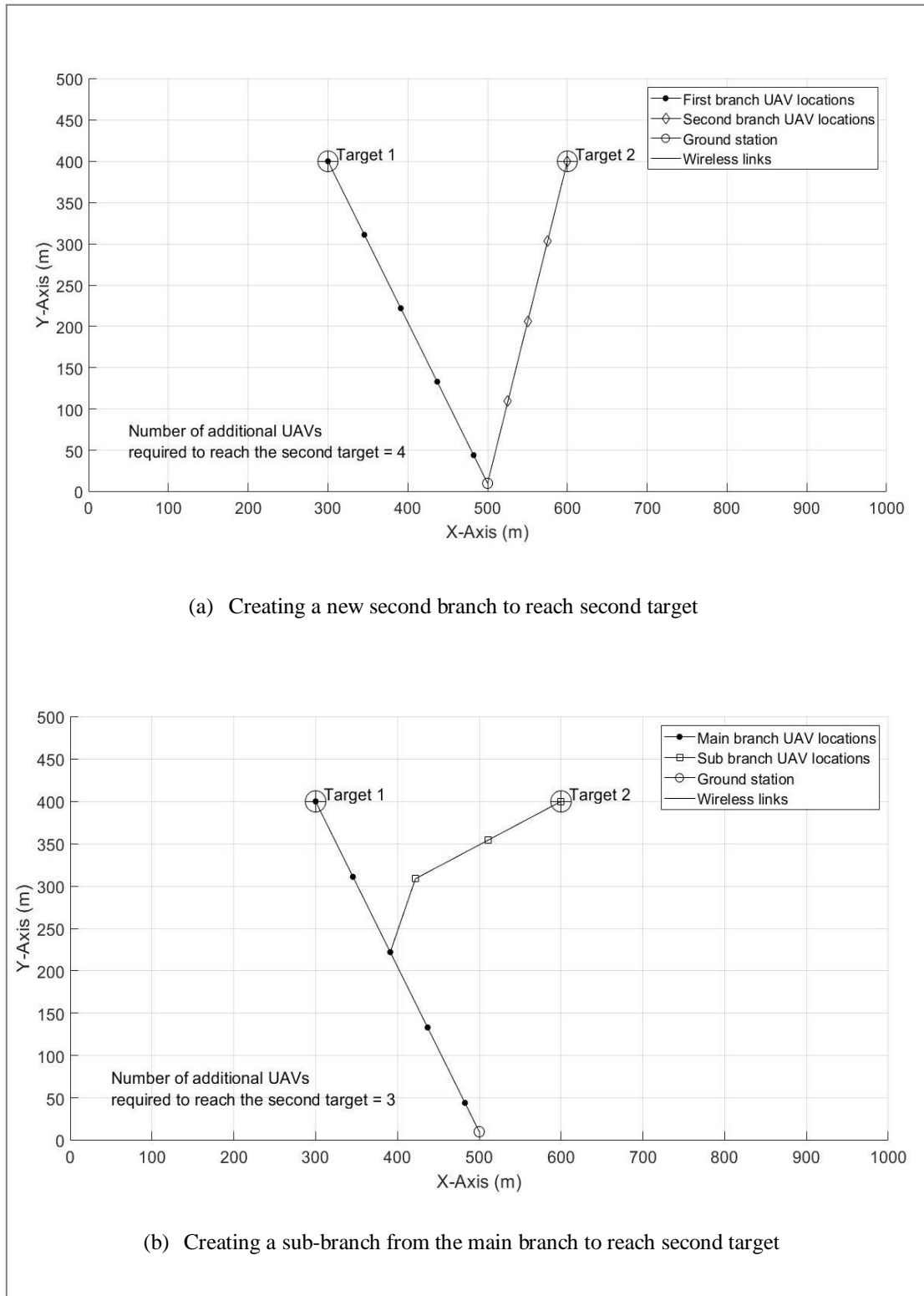
(a)   Creating a new second branch to reach second target

(b) Creating a sub-branch from the main branch to reach second target

Figure 4. Preforming two tasks simultaneously at two distinct locations

To further verify the simulation results, we created sub branches from each node of the main branch to the second target. Table 2 shows the number of additional UAVs required to create a sub branch to reach Target 2 from each UAV of the main branch. It shows UAV1 and UAV2 are

the best nodes to create a sub branch to minimize the total number of UAVs required to perform both tasks simultaneously. However, UAV2 is the closest node to GS out of UAV1 and UAV2. Therefore, creating the sub branch from UAV2 minimizes the relay nodes between the sub branch and the GS, increasing the quality of data transmission.

Table 2: Number of UAVs required to reach Target 2 from each node of main branch

Node of main branch(Refer to Figure 1 for UAV numbering convention)	Number of additional UAVs required to reach Target 2
UAV0	4
UAV1	3
UAV2	3
UAV3	4
UAV4	4
GS	4

The above simulation elaborates the method of minimizing the number of UAVs used to perform tasks at two given targets simultaneously. However, in any practical application the targets are not predetermined, and, hence, the LoD should be able to reach any given two locations in an area of the land. Accordingly, the simplest method to find the minimum number of UAVs required to perform tasks at any given two target locations is to select equally spaced points along the perimeter of the land and calculate the minimum number of UAVs required to reach the two selected points from the border of the land. If there are k number of points along the border, there are $\frac{k!}{2(k-2)!}$ number of combinations of two points. Therefore, the minimum number of UAVs required should be calculated for each combination and the maximum number of UAVs required out of each scenario is the final solution for that specific land. Let us elaborate this method using the following simulation.

Simulation 2: Consider a rectangular field (Figure 5) specified by coordinates (0, 0), (800, 0), (0, 600) and (800, 600) in meters. The GS was located at coordinates (400, 20), and the LoD was required to monitor a maximum of two locations inside the land at any given time. These two locations were arbitrarily selected depending on the requirements of the user. Before carrying out the MATLAB simulation, 280 coordinate points were selected with 10 m gaps along the boundary of the land. If we were to select any two targets out of those selected points, there would be 39,060 combinations of target locations. The simulation was carried out to calculate the minimum number of UAVs required to reach each target combination. Figure 5 shows the target locations, which requires the maximum number of UAVs out of all target combinations. According to the simulation, 15 UAVs can reach any given two targets and perform tasks simultaneously.
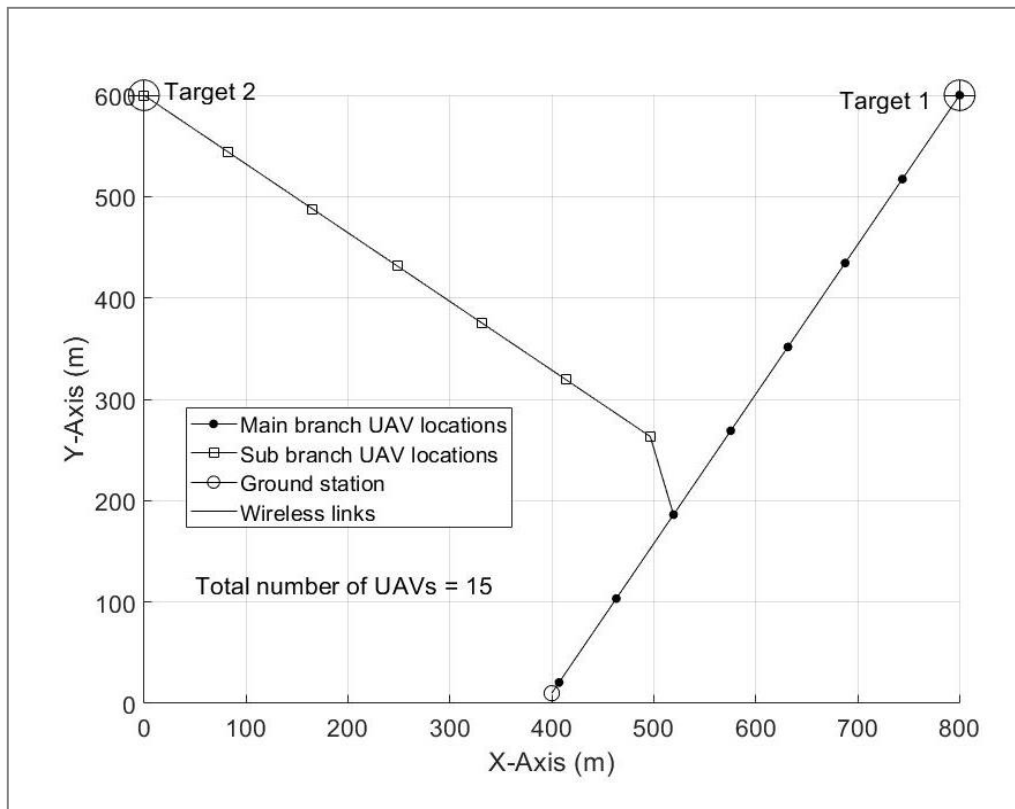
Figure 5. Reaching two targets simultaneously

Let us now use the same method to find the minimum number of UAVs required to reach two arbitrary targets in a given irregular shaped land.

Simulation 3: Consider the field shown in Figure 6 specified by coordinates (50, 0), (200, 400), (500, 550) and (750, 0) in meters. The GS was located at coordinates (400, 20), and the LoD was required to monitor a maximum of two locations inside the land at any given time. These two locations were arbitrarily selected depending on the requirements of the user. Before carrying out the MATLAB simulation, 300 coordinate points were selected with equidistant gaps along the boundary of the land. If we were to select any two targets out of those selected points, there would be 44,850 combinations of target locations. The simulation was carried out to calculate the minimum number of UAVs required to reach each target combination. Figure 6 shows the target locations, which require the minimum number of UAVs out of all target combinations. According to the simulation, 10 UAVs can reach any given two targets and perform tasks simultaneously.
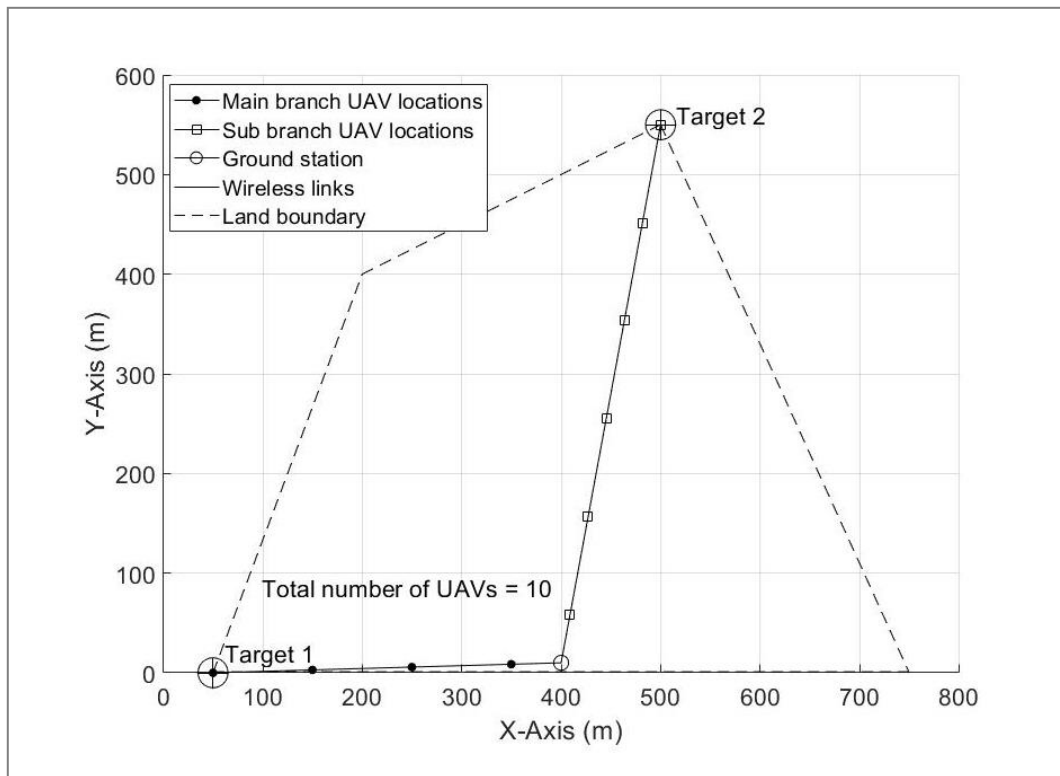
Figure 6: Reaching two targets simultaneously

Let us now consider a scenario where a LoD has to send UAVs to three targets to perform three tasks simultaneously; consider the same situation illustrated in Figure 3 with an additional third target (Figure 7). Let $P_{0F''}$ be the final coordinate point of the third leading UAV. Unlike in the two-target scenario, in the three-target scenario there are three alternative ways that the LoD can send a UAV to the third target. Either the LoD can sub-divide the main branch that reached Target 1, sub-divide the sub-branch that reached Target 2 or create a whole new branch from the ground station. The same approach as that of the two-target scenario can be taken to determine the minimum number of UAVs required to perform tasks at three distinct targets. Perpendicular distances from Target 3 to the existing two branches and to the GS should be calculated, and a third branch should be created along the shortest distance path. A new sub-branch should connect to the closest UAV node located at the GS side of the theoretical sub-dividing point, similar to the two-target scenario.

(a) Three alternative paths to create the third branch

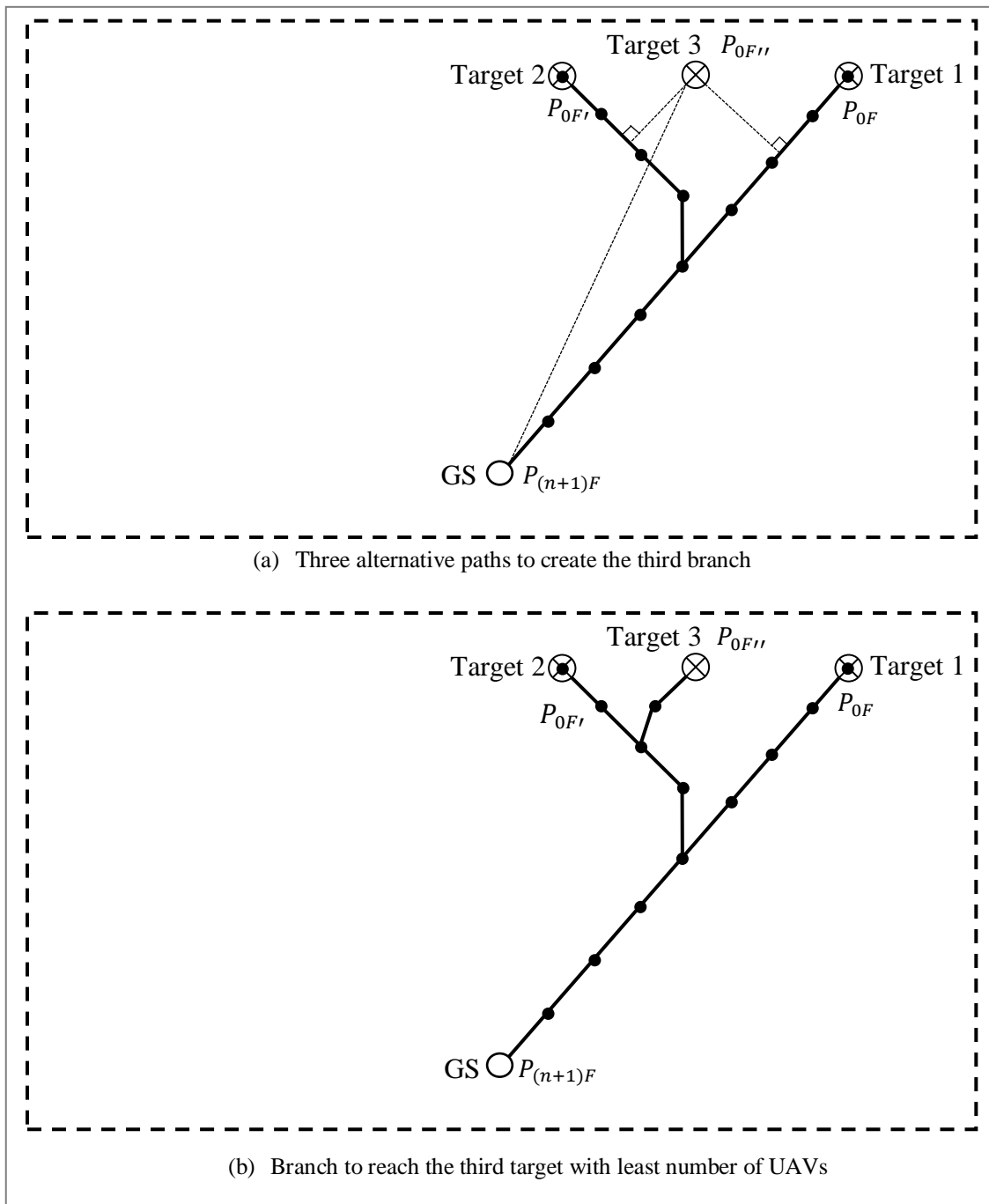(b) Branch to reach the third target with least number of UAVs

Figure 7. LoD reaching three targets to perform three tasks simultaneously

Similarly, the minimum number of UAVs required to perform tasks at any given number of targets can be determined using this method.

3.3. Scanning the Entire Area using a Single LoD Branch

In some UAV applications, the users need to scan the entire land periodically. Geographical mapping, surveying and agricultural crop and disease estimation are some such applications. A single LoD branch can move from one location to another and scan the total area covered by the

LoD branch. Unlike using a single UAV for the whole scanning process, a LoD branch can scan a large area more efficiently, and the scanned results can be streamed to the GS in real-time if the bandwidth allows the transmission.

In order to find the minimum number of UAVs required to scan the entire area of a given piece of land, we must first determine the Field of View (FoV) of a single UAV camera. FoV of a camera is the area captured by the camera's image sensor. The FoV of a camera depends on its Angle of View (AoV), aspect ratio and the distance to the object (Figure 8). In order to find the FoV of a single UAV camera, let us define the following additional quantities.

Let
   i) α and μ be the diagonal AoV and the aspect ratio of the UAV camera, respectively,
   ii) d_O be the distance from camera to the object, and
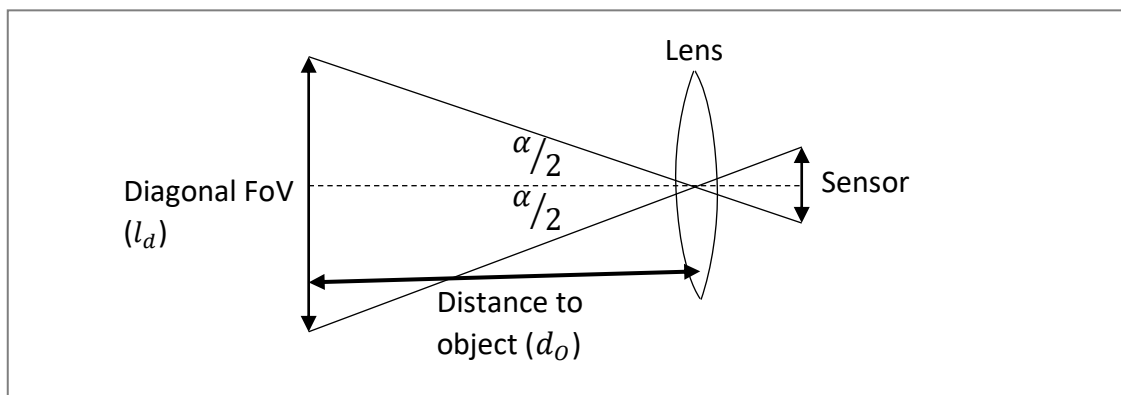   iii) l_d, l_h and l_v be the diagonal, horizontal and vertical FoVs of the UAV camera.

Figure 8. Relationship between FoV, AoV and distance to object

The diagonal FoV of a camera is given by

$$l_d = 2d_O \tan(\alpha/2) \tag{5}$$

The aspect ratio of a camera is the width to height ratio of the video frames and this ratio can be used to calculate the horizontal FoV and the vertical FoV (Figure 9).
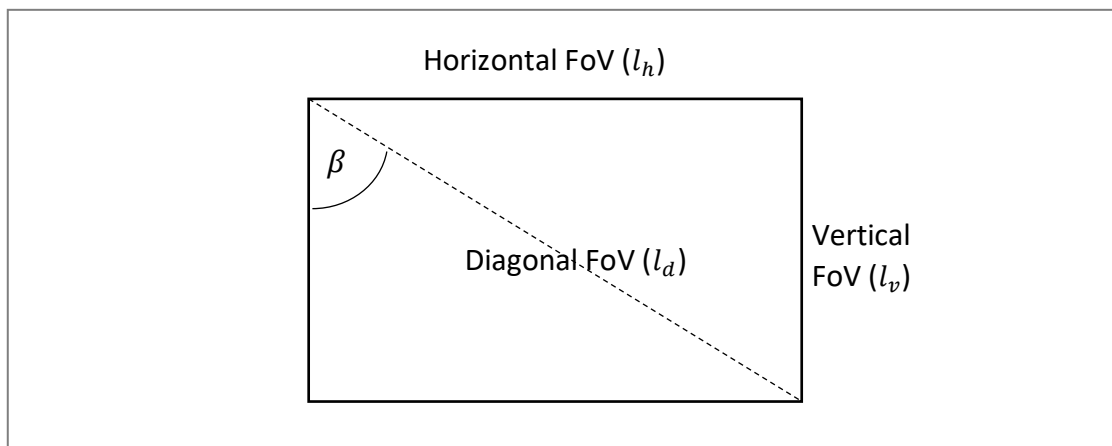

Figure 9. Relationship between Horizontal, Vertical and Diagonal FoVs

Horizontal FoV and the vertical FoV is given by

$$l_v = l_d \cos \beta \tag{6}$$
$$l_h = l_d \sin \beta \tag{7}$$

Where,
$$\beta = \tan^{-1}(\mu) \tag{8}$$

Let us assume that our LoD contain AR. Drone 2.0 UAVs flying over 30 m above ground level. The diagonal AoV (α) of AR.Drone 2.0 camera is 92° and aspect ratio (μ) of the camera video frames is 16:9 [14]. Using (5), (6), (7) and (8), the FoV of the AR.Drone 2.0 is calculated as 52.6 m X 29.4 m ($l_h \times l_v$). Using this FoV, we can determine the minimum number of UAVs required to scan a given area. Let us elaborate the calculation process using the following simulation.

Simulation 4: Consider a rectangular field (Figure 10) specified by coordinates (0, 0), (1000, 0), (0, 500) and (1000, 500) in meters. The GS was located at coordinates (500, 10). A MATLAB plot was generated to represent the land and the GS location. The total area of the plotted land was divided into 50 m x 29.4 m rectangles. The FoV of the AR. Drone 2.0 camera is 52.6 m x 29.4 m. We have intentionally kept a 2.6 m overlap to allow minor fluctuations in the UAV's movements. The movement of the LoD branch was planned in order to direct all the UAVs across these rectangles in an optimal manner. First, the leading UAV node of the LoD branch moved from its initial coordinates (14.7, 425) to coordinates (985.3, 425), and all UAV nodes of the LoD branch moved from left to right and scanned the rectangles represented in blue. Then the leading UAV node moved to coordinates (985.3, 475), and all UAV nodes of the branch moved upwards. Finally, the leading UAV node moved to coordinates (14.7, 475), and all UAV nodes of the LoD branch moved from right to left and scanned the rectangles represented in red. The blue color UAV nodes represent the UAVs that are equipped with cameras, and these UAVs tended to move out of the wireless communication range of GS while moving across the land from one end to another. Therefore, there should be some additional UAVs to relay the communication between these UAVs and the GS. These additional UAVs are represented in red in (Figure 10), and they are not required to be equipped with cameras.
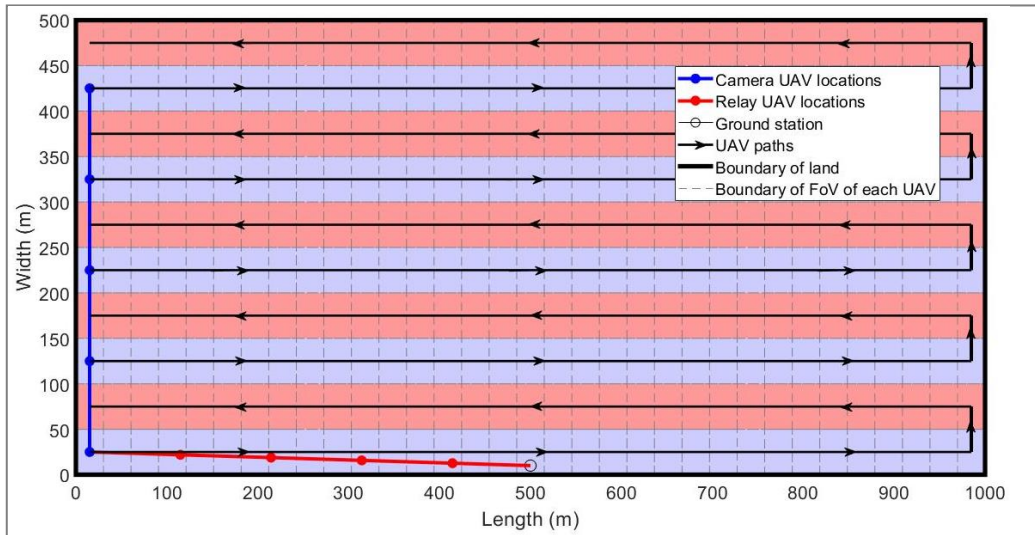

Figure 10. Scanning a rectangular land using a single-branch LoD

3.4. Scanning the Entire Area Simultaneously Using Multiple LoD Branches

As discussed above, if the user employs a single LoD branch to scan a given area, the UAV branch can scan across the land and monitor the entire area. However, this solution is not suitable if someone needs to monitor the entire land simultaneously in real-time. Therefore, there should be multiple LoD branches covering the entire land and monitoring simultaneously at any given time. Let us elaborate on this application via the following simulation.

Simulation 5: Consider a rectangular field (Figure 11) specified by coordinates (0, 0), (1000, 0), (0, 500) and (1000, 500) in meters. The GS was located at coordinates (500, 10). According to the previous calculations, the FoV of a single UAV is 52.6 m x 29.4 m. Therefore, the total area of the land can be divided into 52.6 m x 29.4 m rectangles. Each of these rectangles should be imaged by a UAV, and for maximum accuracy, the UAV should be placed at the center of each rectangle. Therefore, there should be a total of 323 UAVs to monitor a 1000 m x 500 m area of land. According to Figure 11, some UAV branches are located beyond the wireless communication range of the GS. Therefore, there should be a relay of UAVs to create a communication link between each of these branches, and in the figure these UAVs are represented in red. This method requires a large number of UAVs to monitor a given piece of land. As all the UAVs are transmitting their videos to the GS simultaneously, the UAVs and the GS should have large bandwidths to allow such data transmission. Due to these reasons, these types of LoD applications involve heavy costs, making them unsuitable for most commercial applications. However, this method could be useful in defense applications to monitor crime or terrorist attack incidents in real time.
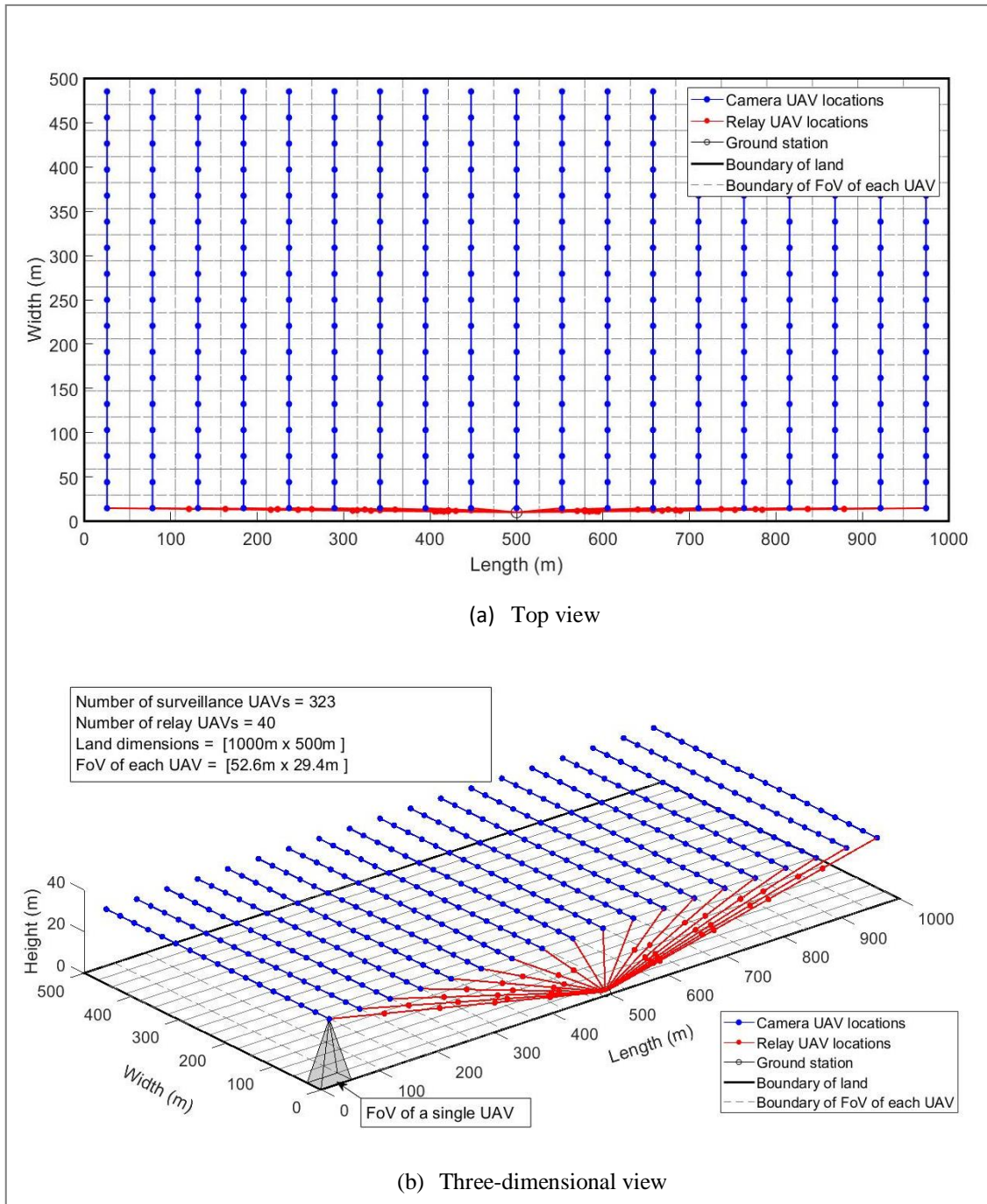
(a) Top view

Number of surveillance UAVs = 323
Number of relay UAVs = 40
Land dimensions = [1000m x 500m]
FoV of each UAV = [52.6m x 29.4m]

(b) Three-dimensional view

Figure 11. Simultaneously monitoring entire area using multiple branches

4. CONCLUSION AND FUTURE WORK

As we have discussed in the introduction, the minimum number of UAVs required for any given task depends highly on the nature of the application. This paper subdivides LoD applications into four different categories: completing a single task at a time, completing multiple tasks simultaneously, monitoring the entire area using a single UAV branch and monitoring the entire area simultaneously using multiple branches of UAVs. We have presented methods of determining the minimum number of UAVs required for each of these application categories.

Completing one task at a time requires the minimum number of UAVs and increasing the number of simultaneous tasks always increases the number of UAVs required for any application. Using the methods discussed, users can estimate the number of UAVs for their requirements. When selling a LoD, all manufacturers need to make the buyer aware of the number of UAVs required for their specific application for them to understand the economic feasibility of the LoD. As such, the presented methods of estimating the minimum number of UAVs are highly useful in the practical implementation of LoDs in commercial applications, such as agriculture. In certain applications such as disaster monitoring or security surveillance, where the economic feasibility is not a critical factor, yet the users should be made aware of the minimum number of UAVs required to perform a given task, in order to prevent facing a shortage of resources in the middle of a critical mission. Therefore, the discussed methods are useful for such applications to complete tasks successfully with no interruptions.

The practical implementation of a LoD is still in progress. Soon after the implementation of the LoD, the proposed method will be used to find the minimum number of UAVs to perform tasks in a specific application scenario. As future work, it is recommended to perform experimental tasks in all four categories discussed in this paper and compare experimental results with the simulation results.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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