MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES
IN PURE AND APPLIED SCIENCES

Effects of UAV Mobility Patterns on Data Collection in Wireless Sensor Networks

Sarmad Kadim Rashed Rashed

MASTER THESIS

Department of Computer Engineering

Thesis Supervisor

Asst. Prof. Müjdat SOYTÜRK

ISTANBUL, 2015

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Sarmad Kadim Rashed Rashed, a Master of Science student of Marmara University Institute for Graduate Studies in Pure and Applied Sciences, defended his thesis entitled "Effects of UAV Mobility Patterns on Data Collection in Wireless Sensor Networks", on September 16, 2015 and has been found to be satisfactory by the jury members.

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APPROVAL

Marmara University Institute for Graduate Studies in Pure and Applied Sciences Executive Committee approves that Sarmad Kadim Rashed Rashed be granted the degree of Master of Science in Department of Computer Engineering, Computer Engineering Program on 05.10.2015 (Resolution no: 2015/22-07).

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ACKNOWLEDGMENT

First and foremost, my sincere thanks and appreciation go to Asst. Prof. Müjdat SOYTÜRK for all of his advice and encouragement throughout my course of study. He supported me at times of difficulty, encouraging me and showing his confidence in me. His invaluable guidance and his enthusiasm for new ideas have led me to have a good attitude toward any research in front of me.

I would like to thank the Turkish government for providing me the national scholarship which was very helpful to complete my graduate study.

Also, I thank my parents, my wife Shaymaa HUSSEIN, my daughter Lujain, and my friends. They were always supporting me and encouraging me with their best wishes special Shaymaa. She was always there cheering me up and stood by me through the good times and bad.

My work would not have been possible without their confidence in me.

September, 2015 **Sarmad Kadim Rashed Rashed**

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Eylül, 2015 **Sarmad Kadim Rashed Rashed**

ABSTRACT

EFFECTS OF UAV MOBILITY PATTERNS ON DATA COLLECTION IN WIRELESS SENSOR NETWORKS

Sensor nodes in a Wireless Sensor Network (WSN) can be dispersed over a remote sensing area e.g. the regions that cannot be accessed by human beings (inaccessible regions). In such kind of networks, data collection becomes one of the major issues. Getting connected to each sensor node and retrieving the information in time introduces new challenges. Mobile sink usage, especially the Unmanned Aerial Vehicle (UAV), is the most convenient approach to cover the area and access each sensor node in such a large scale WSN. However, the operation of the UAV depends on some parameters such as endurance time, altitude, speed, radio type in use, and the path. In this paper, we explore various mobility patterns of UAV that follow different paths to sweep the playground in order to seek the best area coverage with maximum number of covered nodes in less amount of time needed by the mobile sink. We also introduce a new metric to formulate the tradeoff between maximizing the covered nodes and minimizing the operation time for choosing the appropriate mobility pattern. A realistic simulation environment is used in order to compare and evaluate the performance of the system. We present the performance results for the explored UAV mobility patterns.

September, 2015 **Sarmad Kadim Rashed Rashed**

SYMBOLS

$\boldsymbol{d}$ **:** Distance

$\boldsymbol{\alpha}$ **:** Exponent of path loss

$\boldsymbol{P}_{\mathbf{tx}}$ **:** Transmission power

$\boldsymbol{P}_{\mathbf{rx}}$ **:** Reception power

ABBREVIATIONS

ACK : Acknowledgement

CH : Cluster Head

CSMA/CA : Carrier Sense Multiple Access with Collision Avoidance

HEED : Hybrid Energy-Efficient Distributed Clustering

IEEE : Institute of Electrical and Electronics Engineers

MAC : Media Access Control

NIC : Network Interface Card

PHY : Physical Layer

RF : Radio Frequency

RSSI : Receive Signal Strength Indicator

UAVs : Unmanned Air Vehicles

WSNs : Wireless Sensor Networks

WPANs : Wireless Personal Area Networks

LR-WPA : Low-Rate Wireless Personal Area Networks

ECG : Electro Cardio Gram

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1. INTRODUCTION

Traditional sensors became one of the interested areas that researchers focus on it in their researches, and with the advances in the technologies and in micro-electromechanical systems (MEMS) they start to focus on the Wireless Sensor Networks because of some of its characteristics which are low power, low cost, small size and the ability to communicate with each other in short distances [2]. Wireless Sensor Networks differs from traditional sensors because of the deployment of large number of tiny sensors over a large scale sensor area as a networking infrastructure. Deployment of the sensor can be predefined by the network designer or the sensors can be randomly deployed depending on the cases e.g. the area cannot be accessible by humans such as volcanos, tropical forests.

WSNs can be used in various application areas. From environmental monitoring to healthcare, in the agriculture, in hostile action and event detection, WSNs can be utilized [2]. However, there are also some challenges that the designer will face in the construction and the maintenance of the network. Poor communication environment, limited resources (battery, CPU and memory), limited bandwidth appear as the main challenges. To cope with these challenges, clustering is one the promising solution applied in WSN.

For large scale WSNs, data acquisition appears as another major challenge. Long distances between source sensor nodes and the sink node avoid direct communication between each other. Multi-hop communication is used by routing the data to the sink node to collect the data from each sensor node. However, as above mentioned challenges, routing data toward the sink is a costly solution. Instead, the use of mobile sink node which moves within the network to collect data is a better solution with respect to the use of fixed sink node. At this point, there are some important measures have to be considered. Depending on the speed of the sink node and the size of the operation area, the nodes in the network may face the same data acquisition problem. For remotely monitored areas, UAV is the best option to cover all area in a short period of time [3]. On the other hand, UAV has some limitations, e.g. operation altitude, speed, available radios and carrying capability. Endurance time of the UAV can be limited, which may force the UAV to complete its mission within a certain amount of time. To be able to make radio link connection with the sensor nodes, the UAV should be loaded the same type (identical) radios with the sensor nodes. Identical radio use will force the UAV to fly at an altitude to be able to accessible by the sensor nodes. For gathering the data from each node, the UAV has to cover all operation area without leaving any unvisited sensor node. Time to cover all nodes might be longer than the endurance time of the UAV which as a result may leave some uncovered nodes. Therefore, there is a need to explore the behavior and the performance of the network in case of the use of various UAV mobility patterns. Our hypothesis is that depending on the density of the network and the size of the operation area, a better UAV pattern might be determined.

1.1. Problem Statement

UAV mobility patterns have major effect on the coverage and connectivity of WSN. The coverage and connectivity can be considered to measure the Quality of Service of Wireless Sensor Network and how accurate the information is collected from the deployed nodes. Therefore, UAV mobility pattern affects the performance of the network. UAV mobility pattern affects the performance of the network. The main aim in the network is the data acquisition from the deployed WSN. However, due the limitations mentioned, the UAV might not cover all nodes in the operation area. There could be some nodes which might not access the UAV to send its data. UAV may follow a path to reduce the number of uncovered nodes. The UAV flight pattern should also consider the UAV endurance time. Therefore, there is a tradeoff between the operation time of the UAV and the covered nodes. If the effects of the mobility pattern of the UAV to the performance of the network are analyzed, a better mobility pattern can be found.

Our aim in this thesis is exploring the effects of the UAV mobility patterns on the acquisition of the data from the WSN. We modeled various mobility patterns and observed the effects of the mobility pattern on data collection. The contribution of this thesis can be summarized as follows:

- Exploring UAV mobility patterns for covering the sensor nodes in the application area.
- Analyzing the effects of clustering and the UAV patterns on clustering e.g. the number of clusters formed.

- Exploring the best mobility pattern for the minimization of the UAV operation time and for the maximization of the covered nodes.
- Exploring the best mobility pattern to avoid and reduce the number of standalone nodes.

This thesis is arranged as follows. In the second section, related works on Wireless Sensor Networks and the research topics discussed. The related works and earlier studies are discussing the different kinds of clustering algorithms that depend on the UAV to solve the coverage problem by depending on UAV paths in the clustering process. Also the coverage problems and problem statement discuss covering the area with maximum number of nodes and the connectivity to UAV. Application areas and communications in WSNs also discussed in this part. The suggested UAV mobility patterns and the network model of UAV integrated heterogeneous are presented in third section. Simulation and results are discussed and explained in fourth section. In the final section, we conclude our discussion.

2. RELATED WORK ON WSN AND THE RESEARCH TOPIC

The Wireless Sensor Network is built from a large or few numbers of sensors that are connected to each other. These sensors are consisting from some parts to achieve connectivity and data processing: Radio transceiver to provide connectivity with other nodes, Control Processing Unit to process the collected data from the field, Battery to provide energy for all units in the node, and Memory to allow saving and retrieving data. Normally the nodes send their data to a Sink or Base Station and can be Bi-directional or one-directional transmission, the nodes different in size and cost according to the characteristics of nodes and the needs. In the past the researchers focused on Quality of Service and bandwidth in WSN but now days they are focusing on energy consumption. The energy consumed due to two reasons communications and computations. The most drain percentage of energy consumed during communications.

On the other hand the Network topology of sensor nodes in the application zone can be either flat topology or hierarchical topology. In flat topology the nodes serve as routers and send the data to the base station in multi-hop/Single-hop transmission and in the hierarchical topology the sensors arranged into clusters to provide reliability and network scalability where using the clustering is efficient way because it provides good way to overcome data congestion and collisions that will drain the energy quickly from the sensor node. In the environment of Network the sensor nodes can serve different kinds of application areas by sensing the different phenomenon that happen in the application area such as medical, civil, and military [4]. The application areas of WSN explained in the next section.

2.1. Application Areas

Wireless Sensor Network in this areas can serves different functions such as environmental monitoring like (temperature monitoring, humidity, vibration, and flood), healthcare, agriculture, hostile action, event detection (military surveillance, border protection). For example in healthcare the deployed sensor nodes can monitor the patients and help the disabled by collecting their information like (Blood Pressure, Blood sugar, and ECG) using medical sensor. The medical sensor collect these information and send it to a base station like (mobile device) carried by the doctors, to allow the doctors monitor the patients status continuously, then the base station send the gathered data to a medical database where all the information saved . From the database all the medical reports for every patient can be printed or accessed at any time needed [5].

In industrial areas also it can monitor the quality of products and also monitor disaster area. Large number of nodes distributed in inaccessible/accessible areas inside a factory and the nodes start to collect the needed data about the goods, products, and the status of machines like (machine temperature and fuel). The control room collecting the data and analyze it, and in case of any fault happen in any machine a rapid response occur. The benefits of using wireless sensor nodes in industrial areas are reducing the cost, provide mobility, good scalability and reduce the number of problems occur in the factory [6].

In prediction of fires and humidity in forests, the sensor nodes play important role to discover the fire places by monitoring the environment. In this kind of application there are two types of monitoring either depending on Phenomena Detection (PD) in which sensor nodes detect phenomena like a fire location in forest or Spatial Flow Assessment (SFA) in which sensor nodes guess a physical phenomenon like weather humidity forecast [7]. A node still senses the environment and at any event happen it sends its data to the base station like (Fires Track or Helicopter). For example in case of fire happened in a forest the node sends an alert message to the base station that can be (Fires Track).

Monitoring the flood and water level, suppose sensor nodes placed in a dam/tank to monitor the increasing and decreasing in the water levels, water temperature, and pH values. The nodes can prevent the flooding in water by sending the accurate measurements of water levels and/or pH values or sending any fault in any part of dam system to the control unit, this control unit can be a base station or sink [8].

In Military Surveillances [9], Wireless Sensor Network presents a good contribution to monitor the borders or the Battlefield. The sensors collect the data from the monitored zone and send it to the control unit, in this kind of application the sensor supposed to be where and when needed, resistant to jamming, direction finding, and provide end-to-end message security. Research challenges appear here like identification of several simultaneous events and reliable correlation of information from neighboring nodes, classification of objects and events. And major challenges also like spatial coverage of

WSN, Supercomputer Processing for WSNs, and Data mining in WSNs.

Problems occur like network topology, energy consumption at nodes, network scalability, coverage of nodes, and network architecture. An efficient method to use the power efficiently is to organize the nodes into small groups called clusters [10]. These nodes then select a Cluster Head according to many factors such as the residual energy and the proximity to the sink path, these Cluster Heads have residual energy more than other nodes in each cluster, and the main function of these Cluster Heads is to aggregate data that are collected from nodes and send it to the sink node which can be mobile sink or stationary sink. After selecting the Cluster Heads the other nodes become cluster member nodes.

2.2. Communication in WSN and the Motivation of This Research

Communication of the Cluster Heads with the sink can be multi hop or single hop. In multi hop transmission, Cluster Heads that are near to the path of mobile sink consume more power than other Cluster Heads far from path because the load of traffic and data passing through it coming from other Cluster Heads and this exhausting the battery of Cluster Heads, in the same time reduces the reliability of end-to-end due to the network size. Figure 2.1 explains typical multi-hop wireless sensor network architecture.

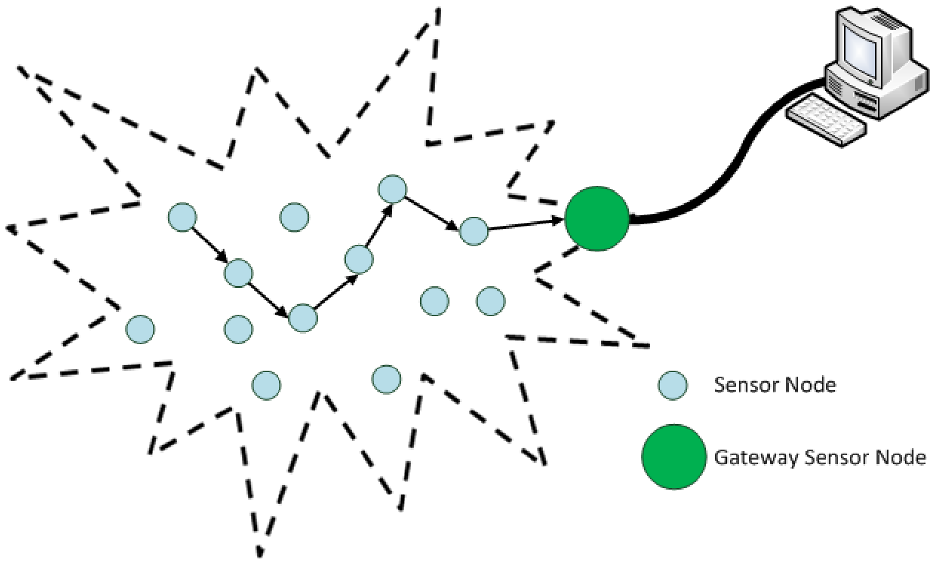


Figure 2.1 Typical multi-hop wireless sensor network architecture

On the other hand using single hop transmission is not benefit-able due to the long distance from Cluster Heads to sink, and between the nodes also, in addition to the short transmission range for nodes. The mobile sink can reduce power consumption at nodes by reducing the communication of multi hop; avoid the redundant transmission and transmission for long distances [11].

Clustering operation is based on classifying the randomly distributed nodes into small clusters, then the nodes inside each cluster start to select a cluster head, the last one will make data acquisition from cluster nodes and send it to mobile sink. In this thesis the cluster formation process depends on the UAV path (i.e. with different UAV paths different clusters are created with different size). Covering all nodes in the operation area is a problem; we suggest different solutions in order to cover all nodes such as using various UAV mobility models like (Circular Mobility, Square Mobility, Angular Mobility, and Tractor Mobility) with different parameters. This mobility patterns allow the UAV to sweep the whole application area to get large number of data from the deployed nodes by covering the total number of nodes. We use intelligent algorithm that depends on the UAV path to provide coverage for all nodes in addition to use the UAV path in the cluster formation process [12]. The process of clustering is different in many proposed algorithms; some depends on residual energy at the nodes as a primary parameter and on the communication cost as a secondary parameter [13], Other approach uses core extraction algorithm [14].

We use standards and models that provide low energy consumption, low data rate, low transmission power, ease of use, reliable data transfer, and low cost provided by the simulation tools used. We used OMNET++ as a simulation environment and MIXIM as a library for models and standards [15, 16]. The used standards are IEEE 802.15.4 complaint nodes [17] and the IEEE 802.15.4 complaint TICC2420 [18] which represent Network Interface Card (NIC) and define the characteristics of Medium Access Control (MAC) and Physical Layer (PHY) used for Low-Rate Wireless Personal Area Networks (LR-WPAN).

2.3. Coverage Problem

Many applications of Wireless Sensor Networks try to monitor all the regions in the area of interest. To ensure best coverage, nodes must be deployed in all regions of interest area by randomly distributing; we can use an aircraft to drop the nodes in the application area to get access all the regions including the far regions also. A simplest idea to achieve total coverage is to turn on all nodes after deploying, but this lead to minimize the network lifetime due to many collisions that happen in the Medium Access Control (MAC) layer because of the large density of nodes. Therefore, it became mandatory to extend the network lifetime during the maintenance of coverage by allowing to some nodes to stay on as a subset of nodes and allow others to sleep.

When the time passing these subsets change until there are no more subsets support coverage. Two types of problem occur in this kind of solution the first one is we need to choose the lower sensor of nodes, and the second is in the scheduling we need to specify for how long we can use the exist subset and which subset is the next. Therefore, three types of well-known coverage techniques have been proposed:

- Barrier Coverage [19]: The nodes arranged in a way to provide minimizing the probability of undetected intrusion. It is used in the detection of movement application whereas it can detect the intruders they are try to cross the border or try to penetrate the protection area.
- Blanket Coverage [19]: attempts to maximize the coverage to monitor the total area. It is trying to monitor every point in the entire area, this kind of coverage increase the detection rate by achieving the static deploying/arrangement of sensor nodes.
- Sweep Coverage [20]: This coverage method tries to cover all the regions in the desirable area within a specified time interval. It is utilizing a mobile node to sweep coverage, whereas the mobile node fly over the area or move inside it to aggregate data from sensor nodes. This mobile node can be UAV or robot.

In this dissertation we depend on the last type (Sweep Coverage) by using UAV to scan all the regions in the area of interest. The scan process mainly using different kinds of explored mobility patterns (Circular Mobility, Square Mobility, Angular Mobility, and Tractor Mobility) to achieve good coverage for deployed nodes (i.e. cover large number of nodes with less amount of time). The coverage with using an UAV affect with some fixed parameters like altitude, speed, and transmission range of UAV. The explored patterns discussed in details in section three. Also many approaches like distributed algorithms proposed to try providing good coverage, these algorithms discussed in the later next sections. The next section (Problem Statement) is discussing the problem of coverage in details.

2.4. The Problem Statement

In Wireless Sensor Networks (WSNs), there are two types of sink nodes (Stationary Sink and Mobile Sink) and due to some limitations in this kind of networks like transmission range of nodes and low power, connectivity problem occur especially in multi hop transmission because of the worst coverage. Using Stationary Sink mostly lead to this problem and the nodes near to Stationary Sink die earlier than other nodes because it drains their energy. Using Mobile Sink was proposed as a good solution to gather data collected by Wireless Sensor Network [21, 22], and the Mobile Sink following a predefined path to provide load balancing and connectivity, in addition to that each node in the area can communicate with the UAV when both in the same transmission range.

The early proposed approaches tried to cover all nodes in the operation area and support best coverage to get a lot of data and best connectivity [12, 23], but the results show that a number of nodes still not covered and became standalone nodes. These nodes in the finalization of clustering process declare themselves as Cluster Heads (CHs) without any member cluster nodes, and this increase the number of cluster heads in the operation area which cause to increase the clusters and this is not efficient.

The normal nodes are not expensive due to the characteristics of these nodes, this cause a connectivity problem when interact with the UAVs. Although the UAVs have additional characteristics and capabilities but they use same radios interface cards to keep contact with nodes in the same transmission range. The main factor that effects on the connectivity and cause the connectivity problem is UAV's altitude, therefore the UAVs must fly over the sensing area in an altitude in which the nodes can be able to communicate with UAVs. In this experiment, we use different altitude values to test the coverage of nodes and its connectivity. Nodes are uniformly distributed over a sensing area with dimensions 2000x2000 m^2, UAV flies over the sensing wireless area with speed 20 m/s and every two seconds it broadcast a beacon message to all nodes. The altitude value specified to 250m because of using IEEE 802.15.4 compliant TI CC2420. According to the datasheet of TI CC2420, there are 8 different power levels and the value 1 mW is the highest power level that support maximum altitude value up to 250m without packet loss when the radio sensitivity is -95dBm and path loss is adjusted to 2.5 [17].

To avoid and reduce the energy exhaustion on communication, and interference at nodes we define that the clusters can be arranged depending on the distance to UAV and neighbor nodes. Nodes that are near to the UAV path can be selected as Cluster Head (CH). This means that all clusters are formed close to the UAV paths in the different mobility patterns. With using the specified power levels for TI CC2420 as mentioned in the datasheet, we can enhance the power exhaustion between nodes and the UAV, and reduce the interference at nodes. The following Equation (1) [24] shows that the interference at nodes depends on the power levels:

$$d = \left(\frac{P_{\mathrm{tx}}.\,\lambda}{16\pi^2.\,P_{\mathrm{rx}}}\right) \quad (1)$$

Where α is the exponent of path loss, P_{tx} is the level of transmission power, P_{rx} is the level of reception power. Receiver Nodes that have higher interference consume more energy; therefore the used approach selects Cluster Head that has shorter distance to UAV and shorter distance to neighbor cluster member nodes in order to reduce the energy consumption at nodes.

We explore various UAV mobility patterns to get best covering to all nodes in the application area. These patterns try to achieve covering maximum number of nodes and take a less amount of operation duration during clustering process. And choose the best mobility pattern in terms of utilization to cover all nodes. The mobility pattern that covers all nodes in the area with a minimal time is considered as the best one.

2.5. Related Works

Several algorithms proposed to cover maximum number of nodes by forming clusters, known as clustering algorithms. In these approaches the main aim is forming well-balanced clusters and avoiding the nodes stand alone. In clustering algorithms, clusters are formed based on the cluster head (CH), so there is a cluster head election algorithm which affects the overall performance. Other objectives of the clustering algorithms are enhancing end-to-end delay, fault tolerance, balancing the load within the network, and increase the connectivity. And using the UAV paths to form clusters close to the paths, provide energy efficiency in Wireless Sensor Networks (WSNs), and to provide a better way for clustering where organizing the nodes into small clusters is the efficient way to achieve total coverage for nodes, better connectivity between the UAV and the clusters, reduce the power consumption at nodes, prolong the network life time, and provide network scalability. Some algorithms are focused on enhancing end-to-end delay, fault tolerance, balancing the loads within the network, and increase the connectivity.

The distributed solutions work by exchanging the information between the sensor and its neighbor node. The utilized information such as available energy in batteries at every sensor node and covered targets are used to greedily decide which sensors remain on. Rounds are used to organize the distributed algorithms so that the set of working sensors is periodically reorganized at the beginning of each round. Below, briefly discussion for some of proposed distributed algorithms.

One of the early studies in clustering and energy efficiency is Low-Energy Adaptive Clustering Hierarchy (LEACH) [3]. In LEACH, a distributed clustering algorithm used to form the clusters. Cluster Head (CH) nodes are selected randomly with a probability value. This algorithm does not guarantee to form stable and same number of clusters at each round. Nodes have the possibility to select same number of cluster head due to the randomness property of random number generator.

Hybrid, Energy-Efficient, Distributed clustering (HEED) [13], is another distributed clustering algorithm. It is a multi-hop distributed Clustering algorithm; it improves the first algorithm for cluster formation. HEED aims to form more balanced clusters and to reduce the energy consumption by considering several parameters. Cluster head election uses residual energy at nodes to select the best node as CH. This algorithm use primary parameters for cluster head selection, first residual energy of each node is used probabilistically to choose the initial set of cluster heads, Second the intra-Cluster Communication cost which is used by nodes to determine the cluster or join. In this algorithm the cluster head are well distributed than LEACH.

ExHEED Extended HEED [14], is an extension to the HEED. It uses a core extraction algorithm to reduce the number of standalone CHs which is high in HEED. It has the same problem with HEED which is the single CH problem, but with using the core extraction algorithm the single Cluster Head (CH) count reduced, although clustering delay and energy consumption reduced.

RSSI-based Hybrid and Energy-Efficient Distributed clustering (rHEED) [12], is a multi-hop distributed Clustering algorithm and improves the HEED [13] algorithm for cluster formation. It uses the Received Signal Strength Indicator (RSSI) for cluster formation and cluster head selection. It has been tested in an environment where the UAV takes the role of mobile sink. It is seen that more nodes are covered with the use of rHEED compared to the others, so in this study, this algorithm has been used to form clusters in WSN. The uncovered nodes can get connection to the closest CHs when the cluster formation process finish, in this way the coverage improved by reducing the number of uncovered nodes. This approach also provides load balancing and energy efficiency using by nodes.

In [25], this approach is an extension to LEACH [3] algorithm. The authors proposed a scheme for node-scheduling which turns off some copious sensor nodes to increase the network lifetime and reduce the energy draining at nodes. In this algorithm the coverage is achieved by depending on the sponsorship idea (i.e. when any node in the network receive a packet from its active sensor neighbor node, the node starts to calculate the maximal section covered by neighbor node) this section called (Sponsored area). And the sponsored area is defined by the nodes that are in the same range of each other. The node turns itself off when the combination of all the sponsored areas of a node covers the coverage disk of the node.

In this dissertation our work differs from early works, we are using different kinds of UAV mobility patterns to cover all nodes in the operation area with minimal time and with maximum number of nods in addition to improve the monitoring quality over time. The designed patterns provide best utilization in order to cover maximum number of nodes in term of time needed. No researches proposed to consider using different kinds of UAV mobility patterns. A distributed clustering algorithm and a single mobile sink node used to cover the nodes that are deployed randomly in the sensing area. The used algorithm forming the clusters depending on the UAV paths by considering the RSSI values of neighbor nodes within the cluster, the energy levels of nodes, the proximity of nodes to the UAV path and their RSSI values to create a balances clusters and produce energy efficiency using.

3. NETWORK MODEL AND EXPLORED MOBILITY PATTERNS

This part, discusses the design of the mobility patterns suggested. To avoid the gaps in the application zone we use a mobile agent, this agent can be (mobile robots or vehicles or airplanes) and its mobility can be randomly, predefined, and autonomously. In this thesis we use predefined mobility paths in order to be able to cover all nodes in the operation zone and also reduce the gaps produced during the clustering operation that depend on the UAV paths.

3.1. UAV Integrated Heterogeneous Network Model

We assume that the nodes are randomly distributed in the operation area as shown in Figure 3.1 and there is a clustering algorithm where a CH is elected in each cluster in the network. Only the CH interacts with the UAV to reduce the overhead and to provide energy-efficiency. We also assume that clusters are formed considering the path of the UAV which is known or learned by the nodes. rHEED [12] algorithm is an example to such kind of clustering algorithm.

In this clustering algorithm, rHEED, nodes form clusters considering both the UAV path and the sensor nodes conditions and proximity to each other. Nodes which are closer to the UAV path are more likely to be selected as CH. On the other hand, a CH has to at range which is closer to its member nodes. Therefore, CH must be both closer to the UAV and its member nodes. CH election process is done distributed by the nodes in the network. The number of the clusters and the size of the clusters are the important metrics in clustering algorithms for stable clustering. It is shown in [12] that rHEED form stable clusters. In rHEED, nodes in a cluster sends their data to their CH. CH aggregates all collected data until UAV approaches to the point with the best transmission distance or conditions. CH measures the best transmission time by evaluating the received signals form the UAV and considering the RSSI values of the received messages. After data transmissions to the UAV, nodes in the network restart to form new clusters considering the UAV path again. In clustering and the cluster head selection, UAV path is not the only parameter. As mentioned, the RSSI value between the member nodes and the candidate CH and the RSSI value of the UAV at the candidate nodes as well as the remaining energy power at nodes plays the major role in the cluster formation and the cluster head selection.

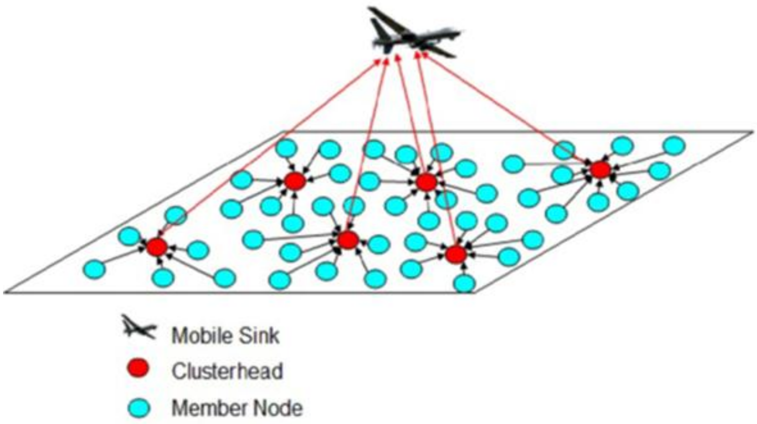


Figure 3.1 "UAV integrated network model [1]"

While the UAV moves over the operation area, an instant sweep region can be formulated as depicted in Figure 3.2. Sweep (coverage) region varies depending on the altitude of the UAV and the transmission range (or transmission power of the UAV and sensor nodes). Maximum coverage radius of the instant sweep region and the sweep width can be calculated as parameter of the maximum transmission power and the altitude of the UAV (4, 5).

$$w = 2\ x\ r \tag{2}$$

$$r = \sqrt{(tx^2 - h^2)} \tag{3}$$

$$w = 2\ x\ \sqrt{(tx^2 - h^2)} \tag{4}$$

$$A = \pi\ x\ (tx^2 - h^2) \tag{5}$$

Where,

h : Altitude of the UAV (m)

r : Coverage radius (m)

tx : Maximum transmission range of the UAV (m)

A : Coverage area

w : Sweep width on the ground (m)

If we assume that there is clustering algorithm e.g. rHEED considering the UAV path, clusters will be formed over/near the UAV path while only the CHs will access to the UAV. As result, even though a cluster member node may have not access to the UAV, it will be covered if its CH has access to the UAV. However, as shown in Figure 3.2 and is calculated in (4) and (5), the sweep region, therefore the number of covered nodes is dependent to the altitude of the UAV. With different UAV altitudes, sweep width will differ, as a consequence affecting the covered nodes and the performance.

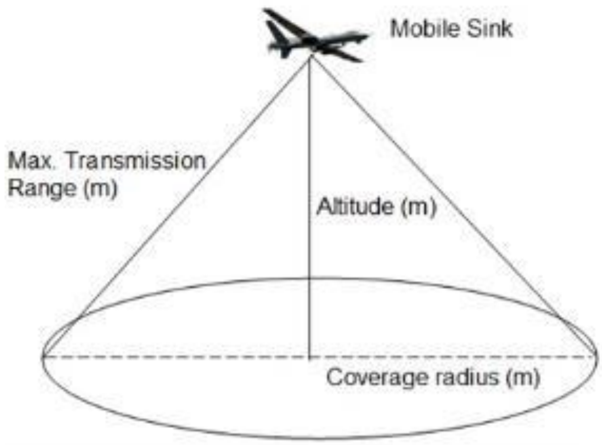
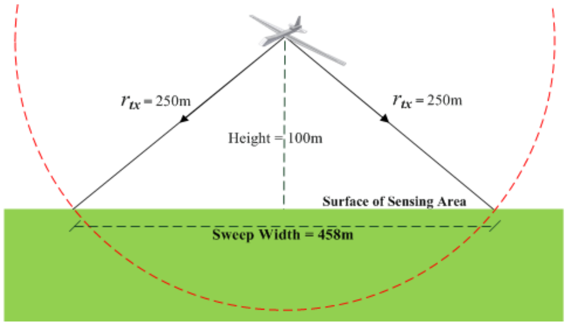
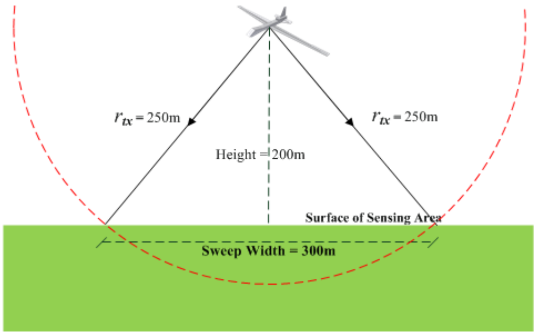


Figure 3.2 Instant sweep (coverage) region of the UAV

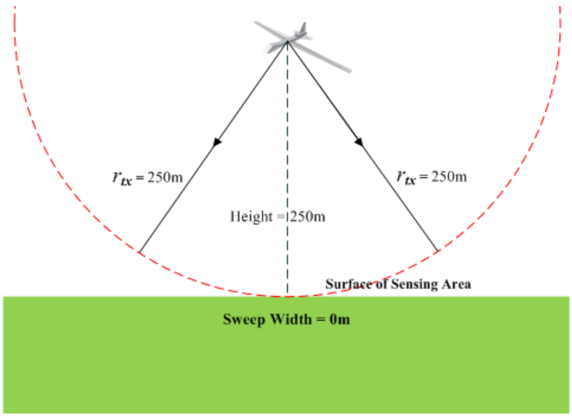
UAV’s sweep widths with different UAV altitudes are shown in Figure 3.3. As seen in the figures, changing the altitude affects the sweep width. Low altitude increases the sweep area and this leads increase in the number of covered nodes. As the altitude increases, the sweep width decreases, consequently reducing the number of accessed (covered) nodes. It also means that at high altitude, there will be less number of candidate CHs and at low altitude, there will be more number of CH candidates. Therefore, the altitude of the UAV is one of the major parameters in data collection in WSN which utilize such a clustering algorithm considering the UAV path.



(a) Sweep with the altitude 100m



(b) Sweep with the altitude 200m



(c) Sweep with the altitude 250m

Figure 3.3 Sweep width depends on the altitude of the UAV. Illustration of the sweep width with different UAV altitudes

In this work, we are analyzing the UAV mobility patterns on the data collection from the WSN. However, as seen, altitude also affects the coverage in the network. In the design of the analyzed WSN network, the following assumptions are considered.

- All nodes are position unaware (i.e. the nodes are not supported with GPS).
- All node distributed randomly in the sensing area.
- The playground is inaccessible area or environment.
- All the nodes are static except the UAV which is mobile node.
- All nodes in the network have similar the same capabilities and resources in terms of memory, processing and communication.

The following sections describe the explored different mobility patterns with the pros and cons for each pattern.

3.2. Circular Mobility Pattern

In this mobility model, as shown in Figure 3.4, the UAV follow a circular path with an angle to draw a circle. Circle center is the center of the operation area. As the angle of the curve gets smaller, smaller circles are drawn. Large circles leave a gap at the center of the circle and small circles leave gaps at the corners of the operation area. When the UAV arrives to the operation area, moves to the starting point and follows the circular path by turning one side with the same angle value. Larger circles increase the circumference of the circles, so the path length and the time to complete the mission. On the other hand, small circles may leave gaps and may cause some uncovered nodes.

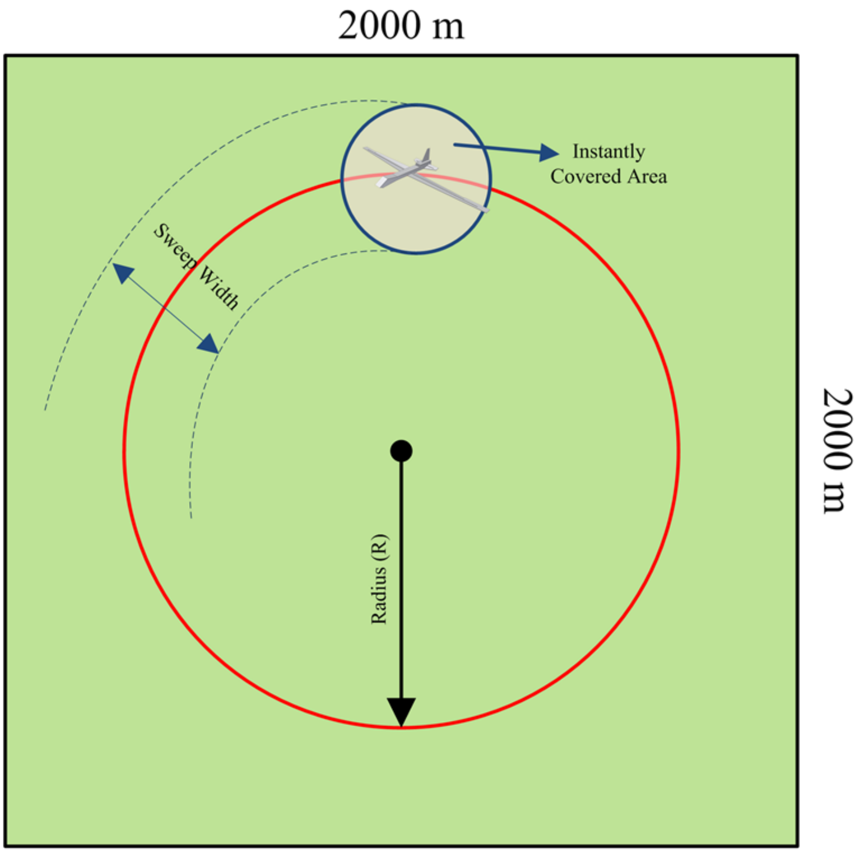


Figure 3.4 Circular Mobility

3.3. Square Mobility Pattern

In this mobility model, as shown in Figure 3.5, the UAV follow a rectangular path. Rectangular/Square center is the center of the operation area. As the length of the edge of the rectangular gets smaller, smaller rectangles are drawn. Large rectangles leave a gap at the center of the rectangle and small rectangles leave gaps outside of the rectangle. When the UAV arrives to the operation area, it moves to the starting point and follows the rectangular path. Larger rectangles increase the circumference of the rectangles, so the path length and the time to complete the mission. On the other hand, small rectangles may leave gaps and may cause some uncovered nodes.

The clusters begin the formation process close to the square path and after finishing the UAV collects the data from every Cluster Head (CH) in its transmission range. This kind of mobility patterns tries to cover maximum number of deployed nodes with less amount of time.

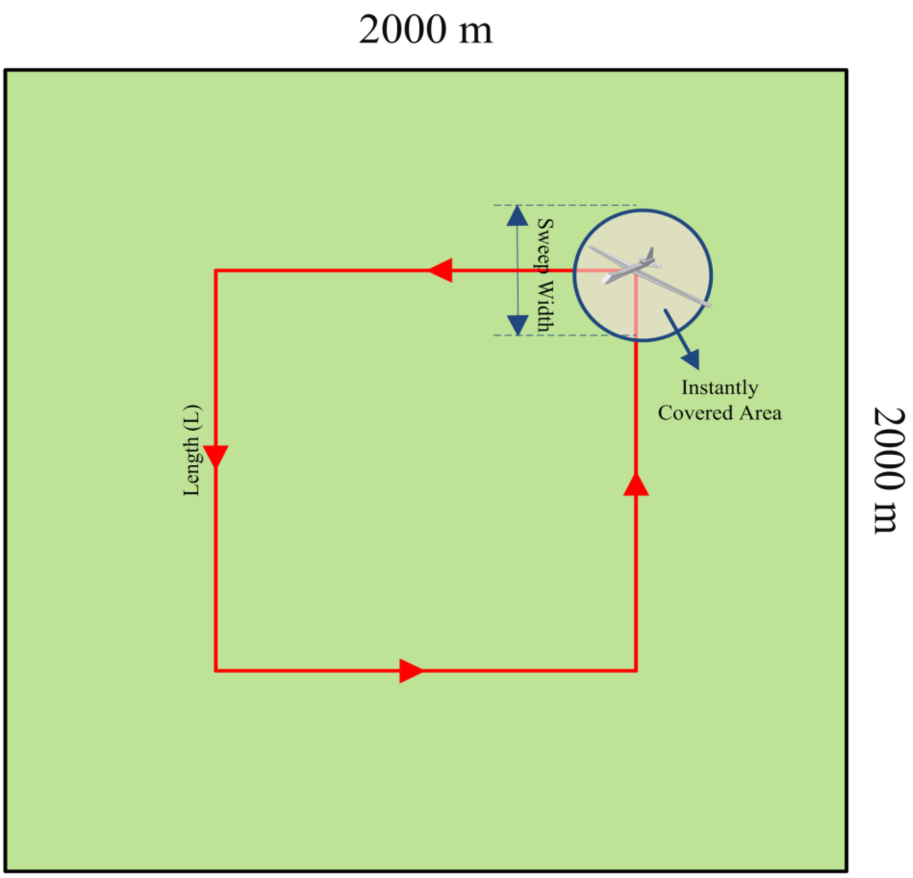


Figure 3.5 Square Mobility

3.4. Angular Mobility pattern

In this mobility model, as shown in Figure 3.6, the UAV follow a flat path, an on arriving to the border of the operation area, the UAV turns its direction to the reverse with a reflection from the border, with an angle value. As the angles value is decreased, more legs are constructed. Large angles leave gaps between the legs. When the UAV arrives to the operation area, it moves to the starting point and follows the angular path. Small angles increase the number of legs, so the path length and the time to complete the mission. On the other hand, large angles may leave gaps and may cause some uncovered nodes.

This kind is best than the previous two patterns, because it reduces the size of gaps which means reduces the number of uncovered nodes in the application zone. With large number of reflection angles the operation duration increase, then the network lifetime decrease.

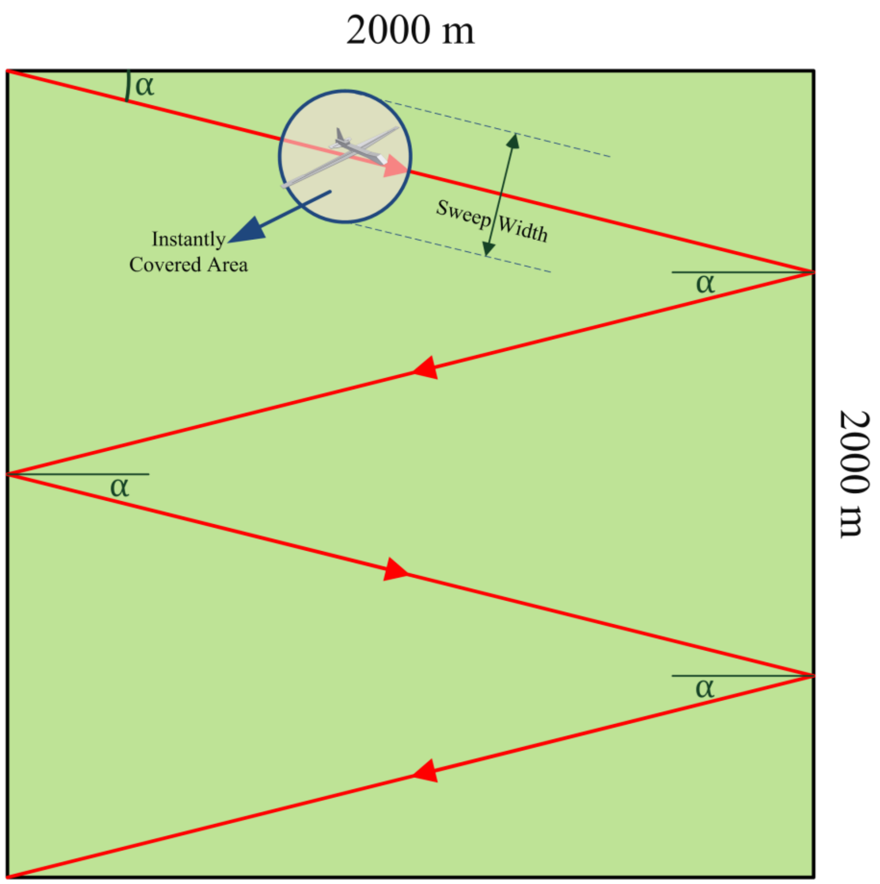


Figure 3.6 Angular Mobility

3.5. Tractor Mobility Pattern

In this mobility model, as shown in Figure 3.7, the UAV follow tracks with a width value between the tracks. As the width between the tracks gets larger, the number of the tracks decreases. Most narrow width leaves no gap covering all nodes while the wider widths may leave gaps between the tracks. When the UAV arrives to the operation area, it moves to the starting point and follows the tracks. Narrower widths increase the number of tracks so the path length and the time to complete the mission. On the other hand, wider width between the tracks may cause some uncovered nodes.

This is considered the best one among all the previous patterns because it sweeps the whole area without leaving gaps or uncovered nodes. Covering all nodes depend on the number of rows/legs that the UAV follow.

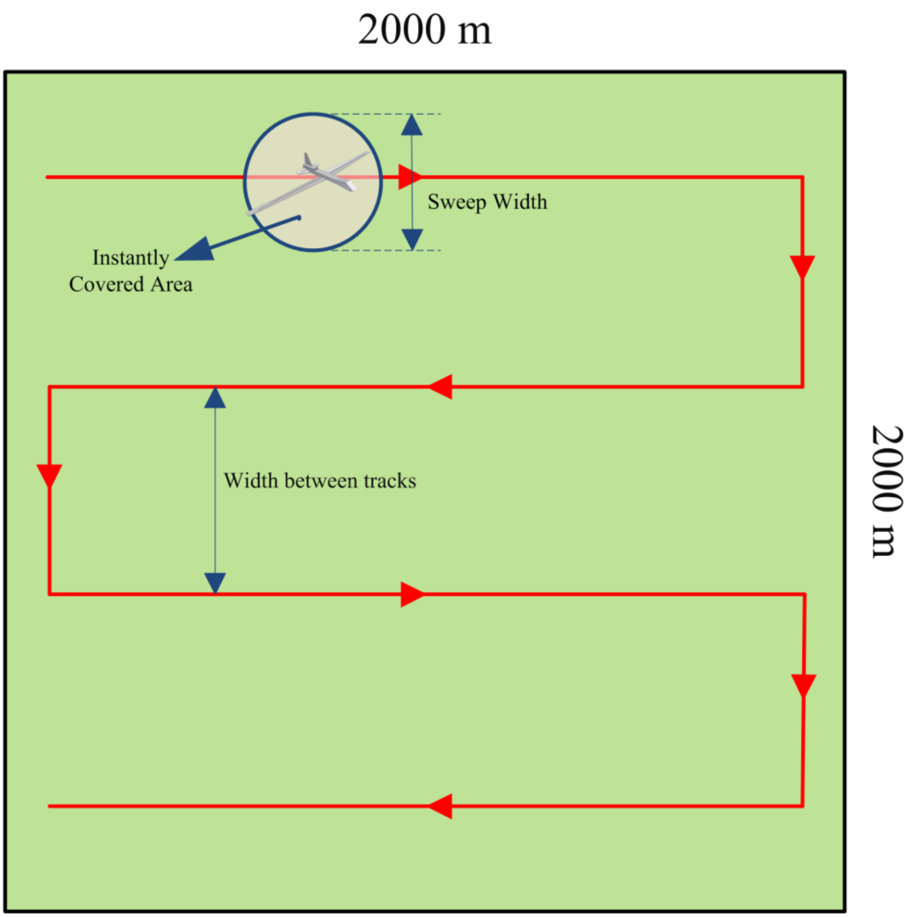


Figure 3.7 Tractor Mobility

4. SIMULATIONS AND RESULTS

We modelled and simulated the network with OMNET++ [15, 26] and MIXIM [16, 27]. The simulator is open source and C++ programming language is used to program the useful models. It provides designing features for Wired and Wireless Networks. MIXIM has good features especially for Wireless ad hoc networks, Wireless Sensor Networks (WSNs), and Vehicular Networks (VANETs), it contains details for models that contain wireless channels, varies power transmission levels, and radio wave propagation.

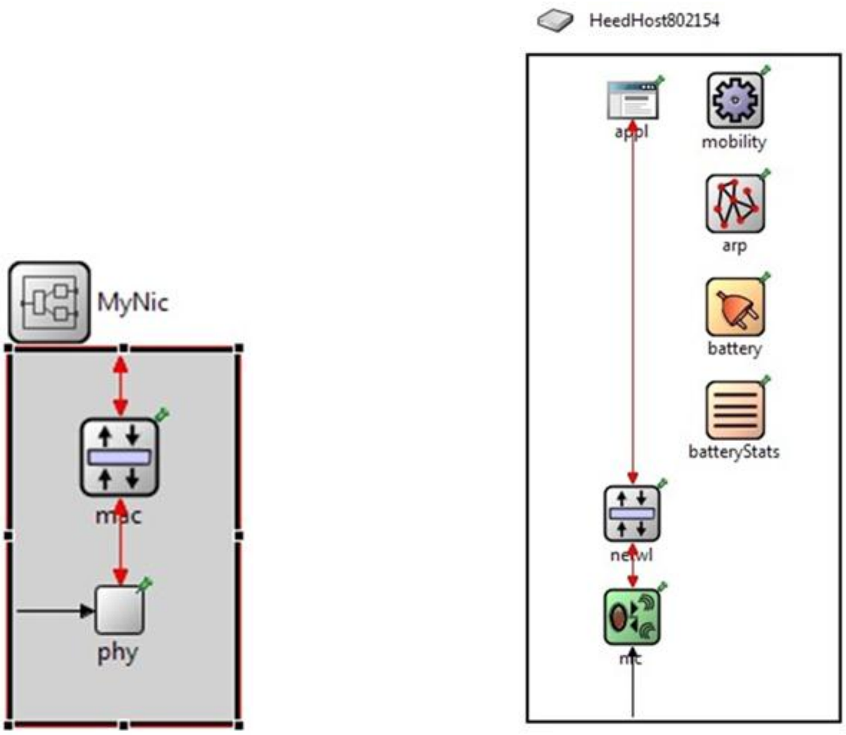
Wireless sensor nodes equipped with IEEE 802.15.4 compliant TI CC2420 radio [18]. The radio model is defined in Section 4.1. UAV has also equipped with the same type radio, TI CC2420, to be able to communicate with the CHs.

Among the UAV models, characteristics of Bayraktar [29] has been modelled and implemented. This type of UAV has ability to fly at low altitude with long endurance duration. Nodes in the network dispersed randomly over 2000m x 2000m area. The UAV flies on the operation area and sweeps the area with the modelled mobility patterns defined in Section 3.

In WSN, nodes form clusters with rHEED [12] algorithm. Only the CHs and standalone nodes communicate with the UAV while the cluster members send their data to their own CH. Clusters are formed depending on the path of the UAV. Because the nodes cannot know the path of the UAV aforetime, with a realistic scenario, UAV makes a blind run over the operation area. Nodes in WSN record the RSSI value of the UAV beacons to use in CH election and cluster formation. After blind run, clusters are formed and in real run (data collection run), CHs send their data to the UAV as defined in [12]. The UAV flies with a constant speed 20m/s, maximum altitude of 250m, path loss exponent 2.5. Nodes receiver sensitivity is set to -95dBm. Table 1 shows simulation parameters.

4.1. Sensor Node Model

We use IEEE 802.15.4 model that is supported by MIXIM [16 , 27] as a sensor node model. This model is equipped with TI CC2420 NIC which contains physical (PHY) layer and media access (MAC) layer to interact with the network (NETW) layer during the operation of the algorithm. It can do many missions like transmitting, receiving, and sleeping. Figure 4.1 (b) shows the model:



(a) TI CC2420 NIC Model (b) IEEE 802.15.4 Model with TI CC2420 NIC Model

Figure 4.1 Sensor node and its interface models

The IEEE 802.15.4 complaint TI CC2420 NIC uses CSMA/CA technique in MAC layer same to IEEE 802.11 but here there is no Request to Send (RTS)/ Clear to Send (CTS) mechanism to prevent the delay and the overhead during communication process in large scale Wireless Sensor Networks (WSNs). Figure 4.1 (a) shows the used model.

4.2. Mobile Sink (UAV) Model

UAV has more operational, functional and resource capabilities than the normal sensor nodes in the application area. While the sensor nodes are stationary on the ground, UAV flies over the operation area at the defined altitude and speed to collect the data from sensor nodes. On the other hand, both node types use the same radio type for communication. Therefore, the UAV has to stay in the transmission range of the sensor nodes for data gathering. As defined before, the radio interface used in the experiments is the IEEE 802.15.4 complaint TI CC2420 NIC device. According to the TI CC2420 radio datasheet [17], the maximum transmission range that can be reached is 250 meters which therefore determines the maximum altitude of the UAV as 250m. There are different kinds of UAVs that depend on different parameters such as speed, endurance, operation altitude, and range of transmission. Among the UAV models, we have used the model of the UAV type Bayraktar [29]. UAV selection is important due to the endurance time of the UAV. Therefore, in this research, one of the main aims is to achieve maximum number of covered nodes with a less amount of operation time.

4.3. Deployment of the Nodes

Nodes in the network dispersed randomly over 2000m x 2000m area. The UAV flies on the sensing area and sweep it by using different mobility patterns. For the nodes starting clustering process, they have to know the mobility path of the UAV in addition to the RSSI values in the construction of clusters and CH election. For these reasons, to let the sensor nodes learn the path of the UAV, the first round is run as a blind run. In the blind run, a sensor node records the RSSI value of the messages received by the UAV. These values will be used to form clusters and select CH which is more efficient to gather data from sensor nodes and to communicate with the UAV. After the completion of the first run, it is known that the clusters area formed according to the RSSI values of UAV. In the actual run, the UAV follows the same path and collects the gathered data from the CHs. Therefore, there are some fixed parameters in addition to the variable parameters that the UAV operates. The UAV flies with a constant speed 20m/s, the maximum transmission range 250m, and the path loss exponent 2.5. Nodes receiver sensitivity is set to -95 dBm. Table 1 summarizes some of the important parameters used in the simulations:

Table 4.1 Simulation Parameters

Parameters	Value
Sink Velocity	20 m/s
Sink Altitude	100m, 150m, 200m, 250m
Sink Beacon Period	2 sec
Number of Sensor Nodes	200 nodes
Max. Transmission range	250m
Simulation Area	2000m x 2000m

4.4. The Effects of Sink Mobility Patterns

For a node to be able to send its data to the UAV either it must have a direct link with the UAV or it must be a member of a cluster where the CH has direct access to the UAV. Therefore, for the data collection in WSN, coverage of the operation area is directly related with the data collection. If a node doesn't have a direct or indirect path to the UAV then it will not be able to forward its data to the UAV. Hence, the data collection problem turns to be a coverage problem.

The UAV mobility patterns have major effects on the coverage and connectivity with nodes in the operation area. The coverage and connectivity can be considered to measure the Quality of Service of Wireless Sensor Network and how accurate is the information collected from deployed nodes.

On the other hand, the time elapsed to collect the data from the WSN is another important metric and aspect. The aim should be collecting as much as data in a shorter period of time. Therefore, in our experiments, six metrics are observed to see the effects of the UAV mobility pattern on the coverage of the operation area. These metrics are:

- **The Number of Covered Nodes**: is the total number of covered nodes in the operation area. It is calculated as the sum of (1) CHs which access to the UAV, (2) cluster member nodes which access to a CH that has access to the UAV, and (3) standalone nodes which access to the UAV.

- **The Number of CHs**: is the total number of CHs including the CHs with some member nodes in the cluster and the standalone CHs without a member node. It gives the number of formed clusters.
- **Time Spent to Cover a Single Node:** is the time UAV spent in the operation area divided by the covered nodes.
- **Utilization**: The ratio of the covered nodes to the total nodes deployed in the operation area. It gives the coverage efficiency.
- **Time and Coverage Efficiency**: It is the ratio of the covered nodes to the time elapsed to cover those nodes.
- **Normalized Time and Coverage Efficiency**. It is normalized value of the Time and Coverage Efficiency. Each pattern may perform differently in terms of covered nodes and time efficiency. In order to use a general metric and scale, the normalized value is much more appropriate.

Each mobility pattern has been tested with various values of the mobility pattern characteristics e.g. various radius values for circular mobility or angle values for angular mobility. Moreover, each mobility pattern has been tested also with different altitude values (100m, 150m, 200m, and 250m). The different altitude values effect on the connectivity between the nodes in the application area and the UAV in addition to its effect on the other performance metrics as described in next section. All results are the averages of 10 runs.

4.5. Performance Results

We will present the performance results of each mobility pattern together for each performance metric in the order given above.

4.5.1. Number of Cluster Heads

Number of cluster heads represents the number of clusters formed. Although less number of clusters is admired in WSN, in such large scale operation areas where the coverage is the major problem, less number of clusters may indicate high number of uncovered nodes. Therefore, although the number of cluster heads gives some valuable information, it has to be evaluated together with the number of covered nodes.

The first results belong to the Angular Mobility pattern. The coverage in the Angular Mobility depends on the angle value, where the angles are used to reflect the UAV when the UAV arrives to the border of the operation area. The UAV is reflected from the border with the defined angle value. Mobility pattern is tested with four different angle values, 5, 10, 15, and 25. These angle values are selected with the purpose to reflect the UAV from the borders after the last reflection of the operation area to follow the reverse path.

It is seen in Figure 4.2 that increasing the angle value leads to decrease in the number of Cluster Heads (CHs). With smaller angles, the number of legs on the path is increased therefore more clusters are formed closer to the UAV path. On the other hand, it is expected to see some gaps between the legs when the angle value gets larger (Figure 3.6). The maximum number of Cluster Heads with UAV access is seen at angle value 5 degree. On the other hand, decreasing the altitude also leads to increase in the number of Cluster Heads. The reason is related with the coverage and sweep width as illustrated in Figure 3.2 and Figure 3.3. At low altitudes, more nodes receive the signals from the UAV to compete to be CHs.

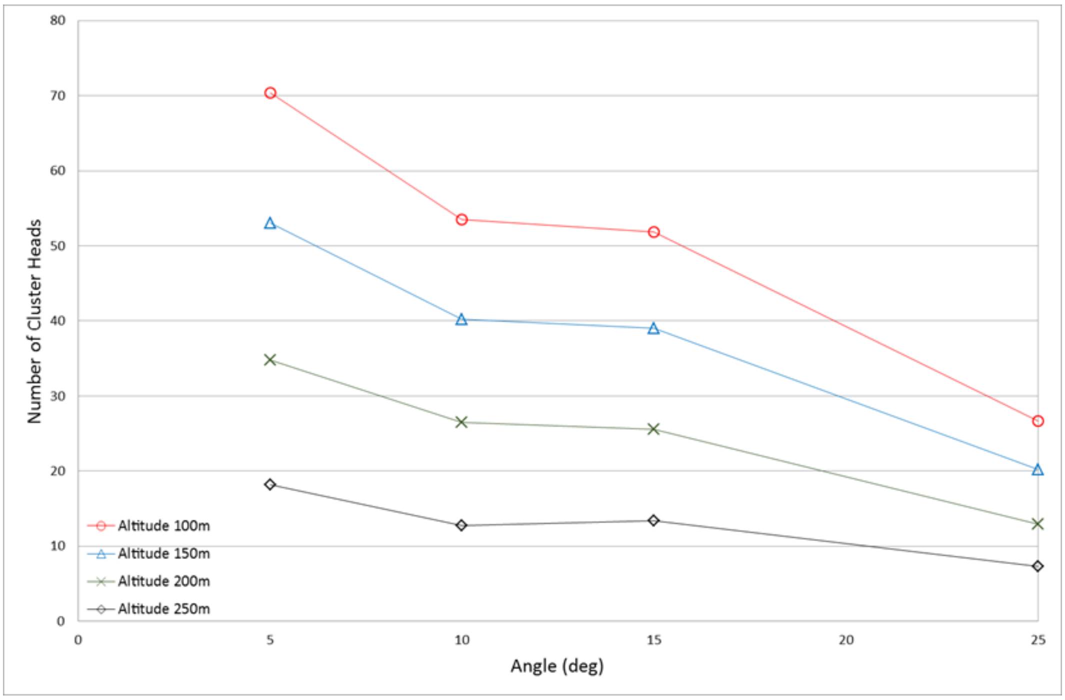


Figure 4.2 Number of Cluster Heads in Angular Mobility

The coverage in the Circular Mobility depends on the circling radius value ***r***, where the center of the circle is the center of the operation area. The simulation is tested with 10 different circling radiuses, starting from 100m to 1000m with 100m increase at each step. With 1000m radius, the UAV touches the center points on the edges of square shape operation area. It is important to see the effects of gaps in the center when the radius is large and the effects of gaps at the corners when the circle is small.

It is seen in Figure 4.3 that increasing the radius of the circling UAV leads to increase the number of Cluster Heads (CHs). With a larger circle, the length of the path is increased therefore more clusters are formed closer to the UAV path. On the other hand, it is expected to see some gaps at the corners of the operation area when the circle gets smaller and at the center of the operation area when the circle gets larger. These gaps increase the number of standalone CHs (the CHs without a cluster member). The maximum number of Cluster Heads with UAV access is seen at radius values 800 and 900m. As the altitude decreases, the UAV sweeps more area therefore the highest number of clusters is observed at 100m with 800 meters circling radius.

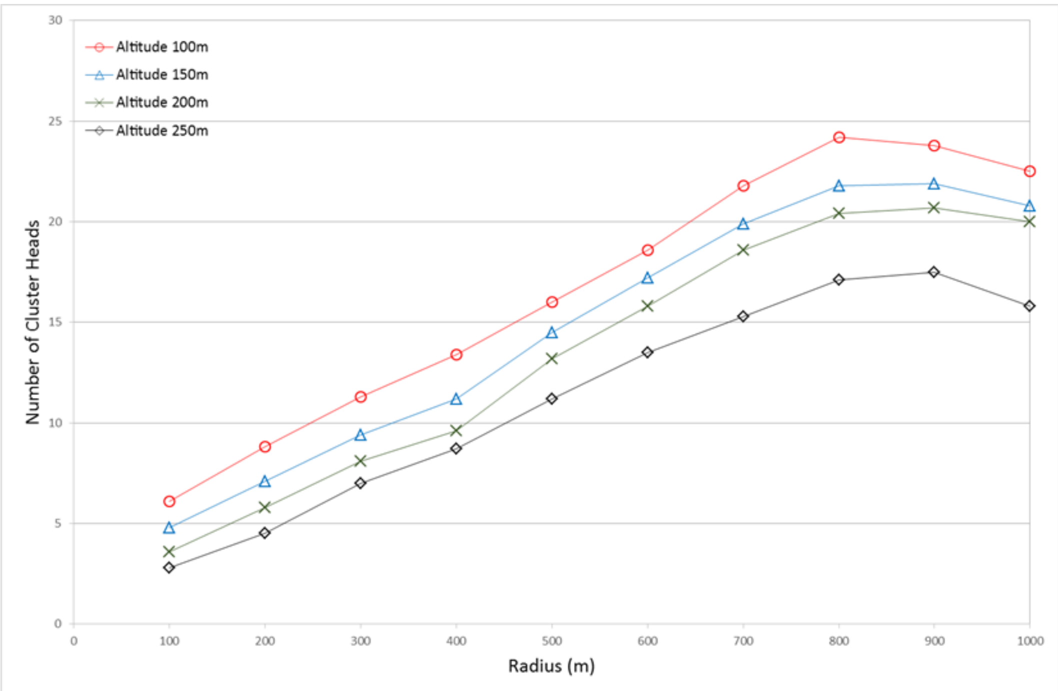


Figure 4.3 Number of Cluster Heads in Circular Mobility

The coverage in the Square Mobility depends on the length of the edge of the square where the center of the square is the center of the operation area. The simulation is tested with 10 different square edge lengths, starting from 200m to 2000m with 200m increase at each step. With 2000m edge length, the UAV follows the borders (edges) of square shape operation area. It is important to see the effects of gaps in the center when the square is large and the effects of gaps at the outside of the square shaped sweep region when the square is small.

It is seen in Figure 4.4 that increasing the length of the squared path of the UAV leads to increase the number of Cluster Heads (CHs). The square mobility is similar to the circular mobility. With a wider square, the length of the path is increased therefore more clusters are formed closer to the UAV path. On the other hand, it is expected to see some gaps outside of the square when the square gets smaller and at the center of the square when the square gets larger. The maximum number of Cluster Heads with UAV access is seen at edge length value 1600m at all altitude values and the maximum is reached with altitude 100m.

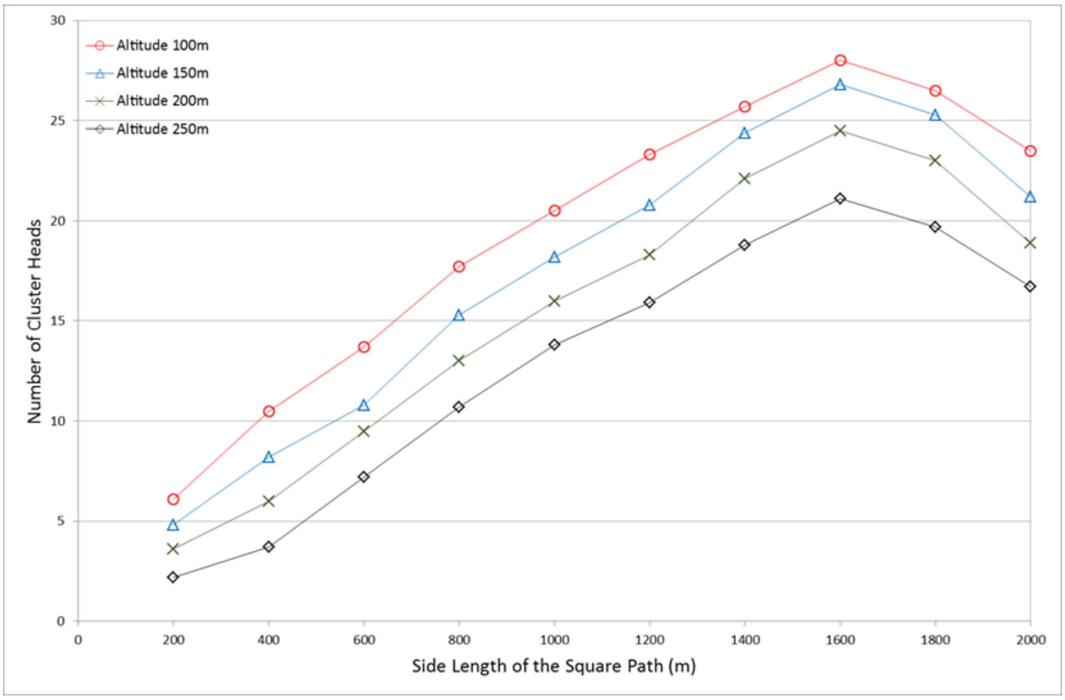


Figure 4.4 Number of Cluster Heads in Square Mobility

The coverage in the Tractor Mobility depends on the width between the tracks, as the width between the tracks increases the number of tracks decreases.

The simulation is tested with 10 different widths between long legs (tracks), starting from 200m to 2000m with 200m increase at each step. With 2000m width, the UAV crosses the operation area at the center from one to the other end. As the width of the tracks gets smaller the number of tracks increases. With less number of tracks, there could be some gaps in the operation area.

It is seen in Figure 4.5 that increasing the width of the tracks leads to decreases the number of Cluster Heads (CHs). With a narrow width between tracks, the length of the path is increased therefore more clusters are formed closer to the UAV path. On the other hand, it is expected to see some gaps between tracks when the width between tracks gets larger. The maximum number of Cluster Heads with UAV access is seen at width value 200m with the UAV altitude value 100m.

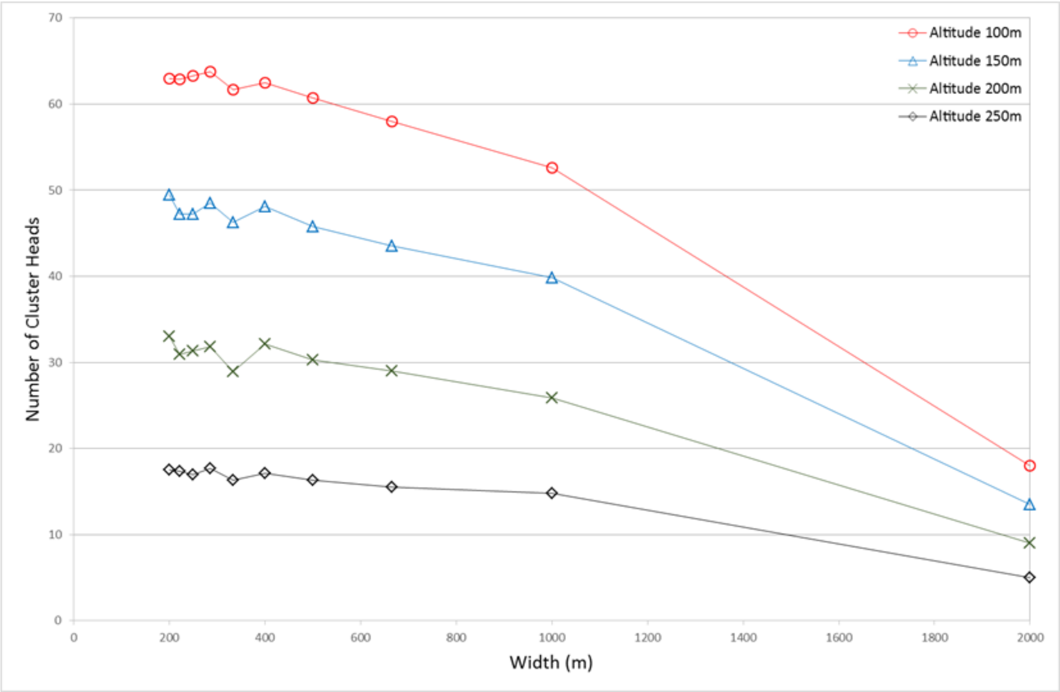
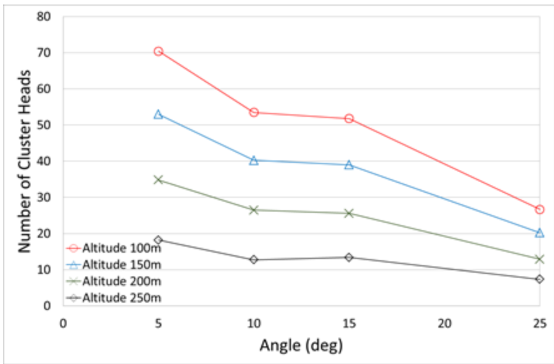
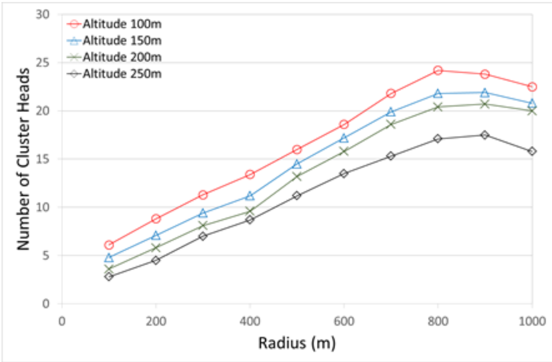


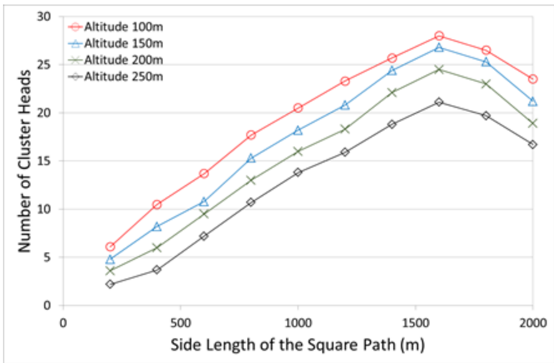
Figure 4.5 Number of Cluster Heads in Tractor Mobility



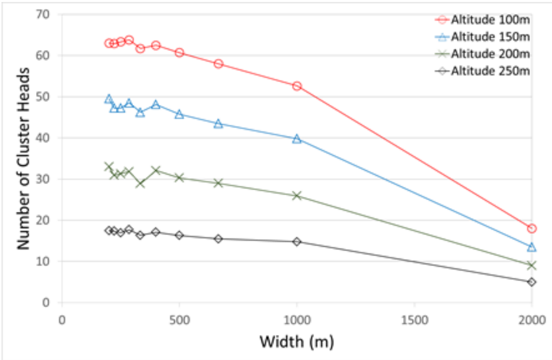
(a) Angular Mobility



(b) Circular Mobility



(c) Square Mobility



(d) Tractor Mobility

Figure 4.6 Number of Cluster Heads in All Mobility Patterns

Figure 4.6 shows the Number of Cluster Heads in all mobility patterns. It is used to show the differences clearly and to alleviate the conflict in the use of different parameters in the different mobility patterns, e.g. radius versus width.

As seen in the figure, the maximum numbers of cluster heads are seen at the tractor mobility and angular mobility. It is also seen that the results for tractor mobility and the angular mobility are very similar to each other, where, on the other hand, the results for circular mobility and square mobility patterns are very similar to each other.

As mentioned previously, it is essential to consider the number of covered nodes with the given results above to deduce a conclusion on coverage and clustering.

4.5.2. Number of Covered Nodes

Figure 4.7 - Figure 4.10 show the results for the number of covered nodes in each mobility pattern. Figure 4.7 shows the number of covered nodes in Angular Mobility. It is seen that as the angle grows the number of covered nodes decreases. When the angle grows, less number of UAV legs is constructed over the operation area. With less number of legs, the UAV sweeps less area. Therefore, at the angle value 5 degree and altitude 100m, 197 of 200 nodes are covered with the maximum value.

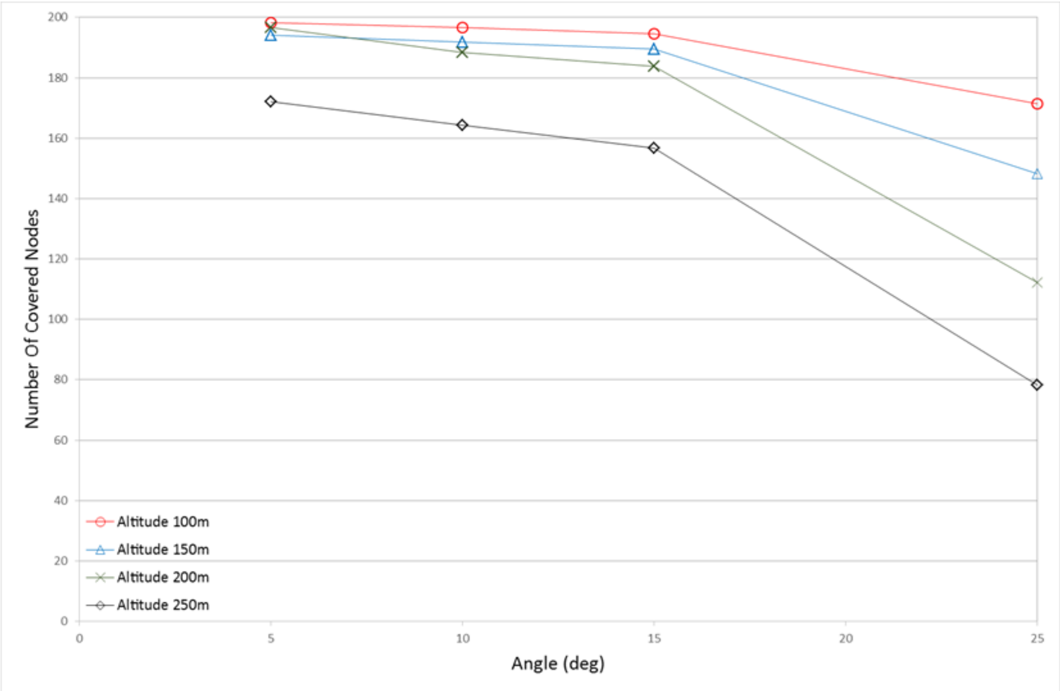


Figure 4.7 Number of Covered Nodes in Angular Mobility

For all angle values except 25, the numbers of covered nodes are very closer to each other. But at the angle value 25, the number of covered nodes reduced significantly especially for the altitudes 250m and 200m. When the covered nodes are compared according to the altitude, it is clearly seen that low altitude covers more nodes. Because the altitude 250m is also the maximum transmission range of the radio, only those nodes under the UAV path are selected as the cluster heads. That's the main reason of less number of covered nodes at the altitude 250m. When the number of legs is reduced due to larger angle values, the number of covered nodes is reduced more and more.

Figure 4.8 shows the number of covered nodes in Circular Mobility. It is seen that as the circular path grows the number of covered nodes increases until the radius value 700m, and then decreases slightly. At radius 700m and altitude 100m, most of 200 nodes are covered. When the radius grows, the path length of the UAV increases. This leads to the UAV sweeps more area to access more nodes and cluster heads. As the radius grows up to 700m, the number of covered nodes increases, but after 700m it starts to decrease slightly. The reason is related with the gaps inside and outside of the circle. When the radius and therefore the circle are small there are gaps outside of the circle where the UAV cannot cover any node. As the circle grows, gaps get smaller. However, after 700m, the gaps outside of the circle are at minimum or no gap exists but new gaps appear at the center of the circle. That is the reason of the increase in the number of covered nodes until radius value 700m and decrease after that.

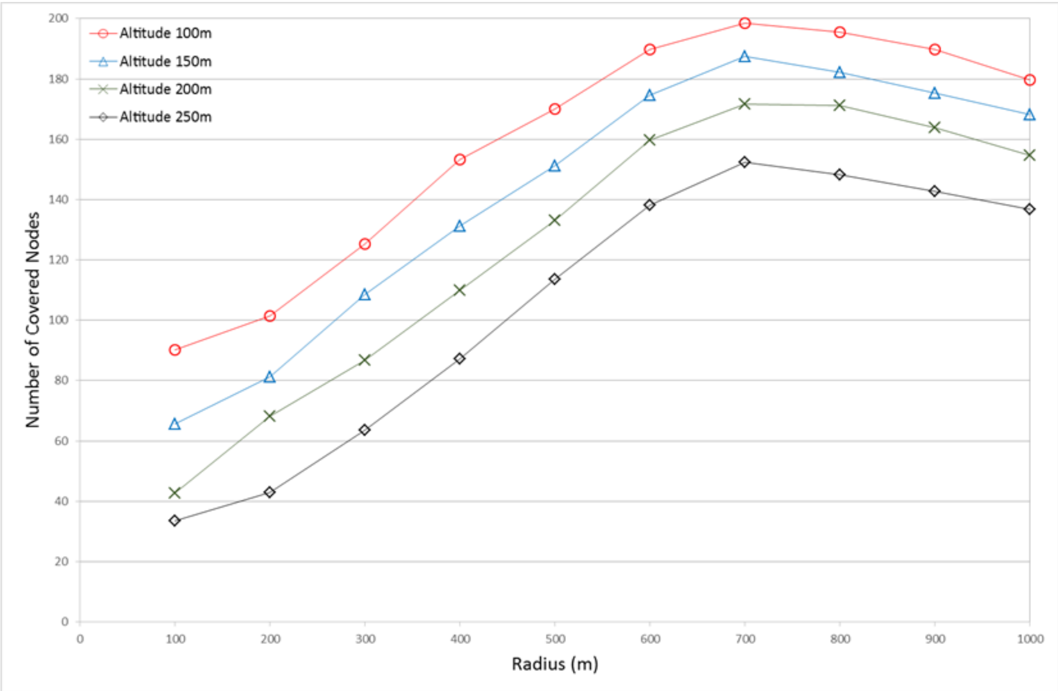


Figure 4.8 Number of Covered Nodes in Circular Mobility

When the altitudes are compared with each other, it is seen that all altitudes perform similarly with some constant difference between each other. Altitude 100m performs better than all.

Figure 4.9 shows the number of covered nodes in Square Mobility. It is seen that as the square path increases the number of covered nodes increases until the length value

1200m, and then decreases slightly. At side length 1200m and altitude 100m, most of 200 nodes are covered. When the side length grows, the path length of the UAV increases. This leads the UAV sweep more area to access more nodes and cluster heads. As the length grows up to 1200m, the number of covered nodes increases, but after 1200m it starts to decrease slightly. The reason is related with the gaps inside and outside of the square. When the side length and therefore the square are small there are gaps outside of the square where the UAV cannot cover any node. As the size of the square grows, gaps get smaller. However, after 1200m, the gaps outside of the square are at minimum or no gap exists but new gaps appear at the center of the square. That is the reason of the increase in the number of covered nodes until side length value 1200m and decrease after that.

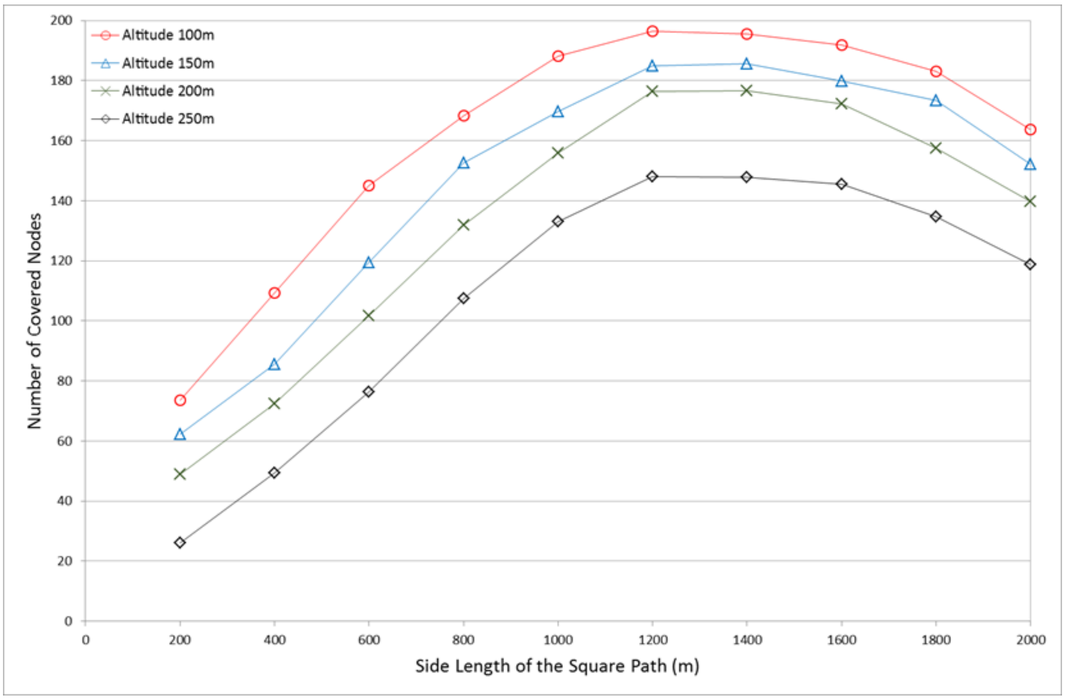


Figure 4.9 Number of Covered Nodes in Square Mobility

When the altitudes are compared with each other, it is seen that all altitudes perform similarly with some constant difference between each other. Altitude 100m performs better than all. It is also noticeable that the performance of square mobility is very similar to the circular mobility.

Figure 4.10 shows the number of covered nodes in Tractor Mobility. It is seen that as the width between the tracks of the tractor path grows, the number of covered nodes decreases until width value 1000m and then doesn't change significantly. At width value 200m and altitude 100m, most of 200 nodes are covered.

When the width between the tracks grows, the path length of the UAV decreases. This leads the UAV sweep less area, eventually to access less number of nodes and cluster heads. As the width grows up to 1000m, the number of covered nodes decreases sharply, but after 1000m it starts to decrease slightly. The reason is related with the gaps between the tracks. When the width is small there is no gap between the tracks where the UAV cover most of the nodes. As the width grows, gaps get larger that causes the decrease in the number of covered nodes.

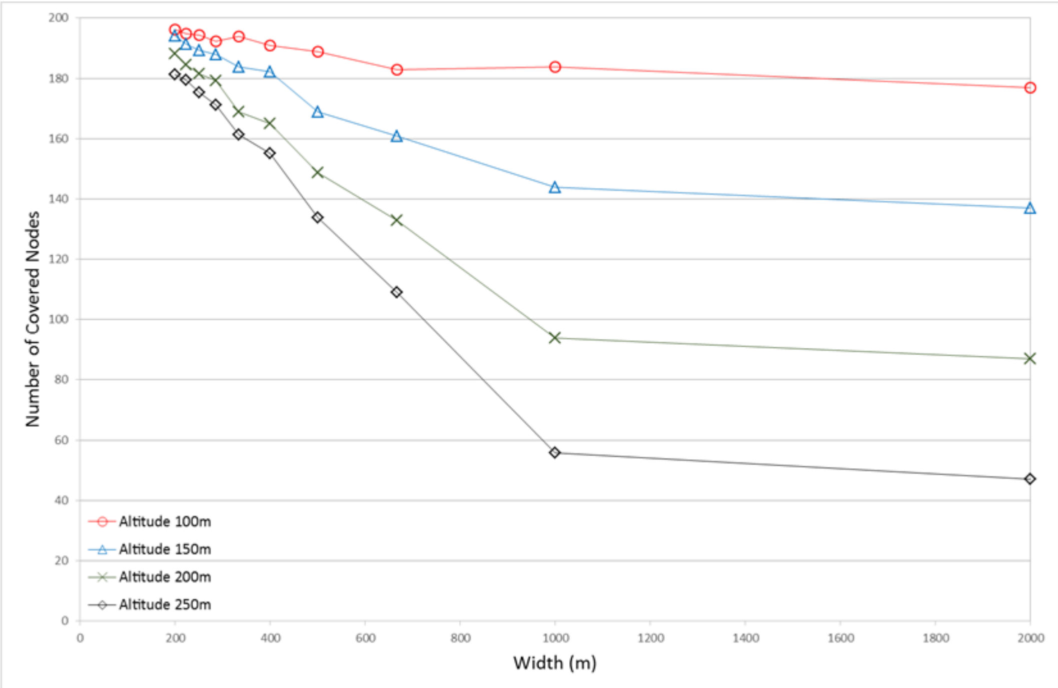
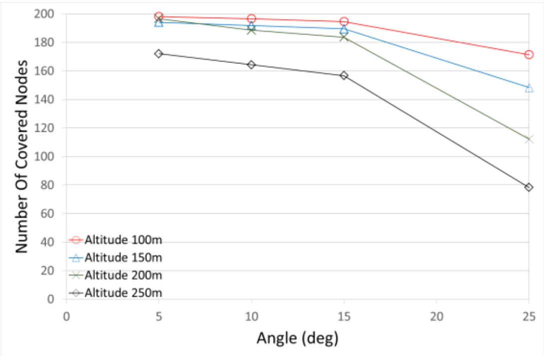
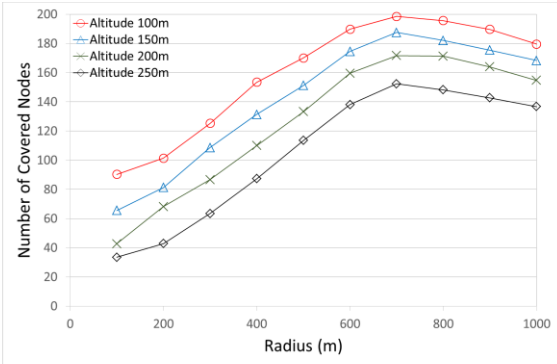


Figure 4.10 Number of Covered Nodes in Tractor Mobility

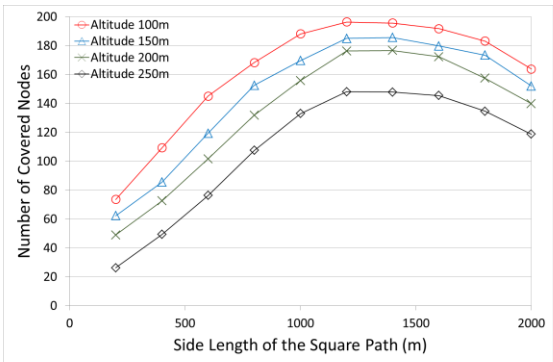
When the altitudes are compared with each other, it is seen that altitude 100m outperforms the others. Altitude 250m is affected much more from the conditions mentioned above compared to the others.



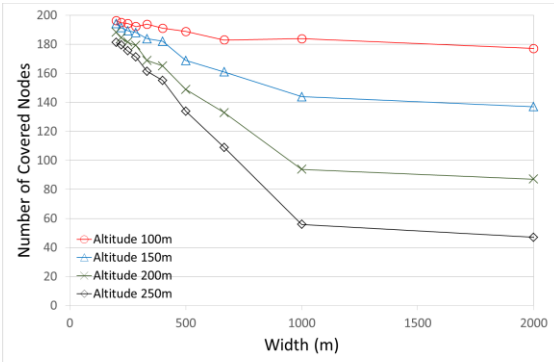
(a) Angular Mobility



(b) Circular Mobility



(c) Square Mobility



(d) Tractor Mobility

Figure 4.11 Number of Covered Nodes in All Mobility Patterns

Figure 4.11 shows the number of covered nodes in all mobility patterns. It is used to show the differences clearly.

As it seen in the figure, the maximum number of covered nodes is seen at the altitude of 100m in all mobility patterns. When the mobility patterns are compared, it is seen that at 100m altitude, angular mobility and tractor mobility results are not affected too much. However, at other altitudes, the results varies a lot depending on both the performance parameter e.g. circle radius or angle, and the altitude. Altitude 250m is affected much more compared to the others, especially for the tractor mobility.

As mentioned previously, the results of the circular mobility are very similar to the square mobility but the circular mobility performs better than square mobility.

4.5.3. Time Spent to Cover a Single Node

In data collection from the WSN, one of the main aims is covering more nodes and the other one is covering the nodes as quickly as possible in a shorter time. Every node in the network could be covered without leaving a gap in the network. However, it increases the path of the UAV and the time to operate in the operation area. Therefore, to avoid unnecessary time spent in the area, it is essential to observe how much time is spent in the area and how much time is spent to cover a single node. It is worth to observe because if only a few more nodes are covered by increasing the path of the UAV a lot and the operation time very much, then it may not be an acceptable solution. Therefore, it is really important to see whether it is necessary to let the UAV continue its operation on the area to increase the number of covered nodes or let the UAV access to a number of nodes but within a short period of time.

The formula for the Time Spent to Cover a Single Node can be derived as follows:

$$Time\ Spent\ per\ Covered\ Node = \frac{the\ time\ UAV\ spent\ in\ the\ operation\ area}{the\ number\ of\ covered\ nodes} \quad (6)$$

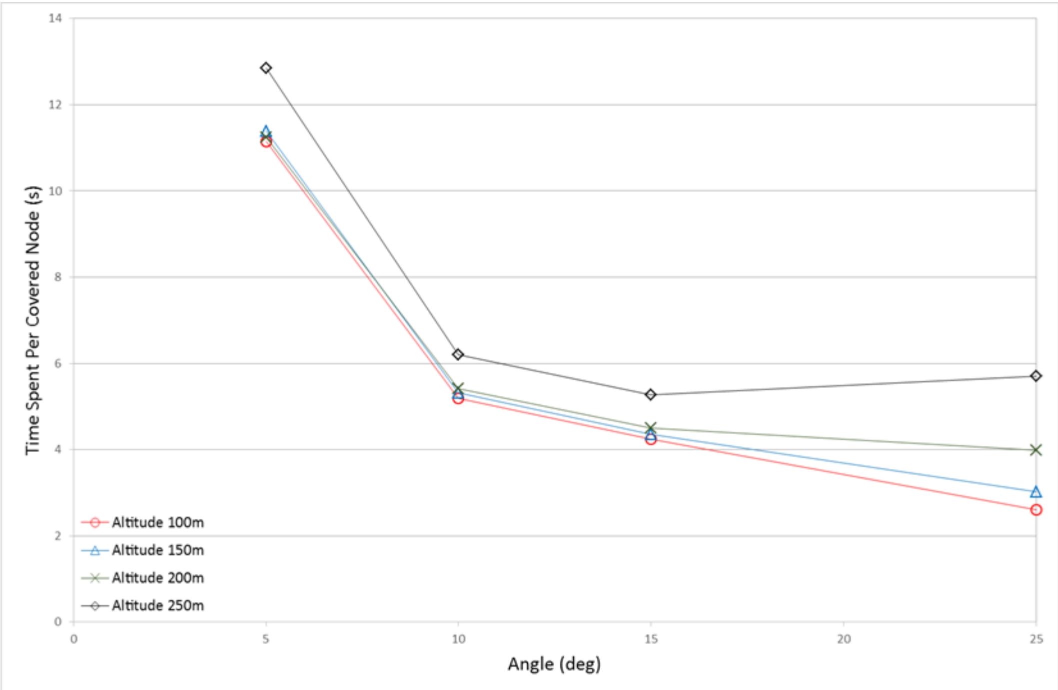


Figure 4.12 Time Spent per Covered Node in Angular Mobility

Figures 4.12-4.15 show the time spent per covered node for all mobility models with various altitudes. Figure 4.12 show the time spent to cover a single node in Angular Mobility. It is seen that as the angle value increases (path length decreases), the time spent to cover a single node decreases sharply, and then continues to decrease slightly after angle value 10 for all altitude values. At angle value 25 degree and altitude 100m, the time spent to cover a single node is at minimum.

Except altitude 250m, all altitudes present similar results. Results for 250m are much higher compared to the others. The reason the same mentioned in other performance metrics. On the other hand, it is seen that the minimum time spent per covered nodes is observed at angle value 25 at all altitudes. However, when we compared with the number of covered nodes, angle value 25 performs the worst results in terms of the number of covered nodes. In this case, there is a dilemma in choosing the best mobility model whether the number of covered nodes or the time spent per covered node should be selected as the decision metric. Therefore, a new metric Time and Coverage Efficiency metric is defined and will be presented later.

Figure 4.13 show the time spent to cover a single node in Circular Mobility. When the UAV follows a path e.g. circle, the path length depending of the mobility type becomes important. As the path length increases, the UAV will spend more time on air. However, depending on the clustering algorithms and the UAV path, more stable and balanced clusters can be formed. Therefore, preferred pattern can be selected based on the time per node. Here, as it is seen, when the path length increases, time spent to cover a single node increases, but then doesn’t increase due to more covered nodes, and then increases again.

The minimum time spent per covered node is observed at the radius 100m. However, again the same decision issue arises. With the radius 100m, circular mobility performs the worst results for the number of covered nodes. Therefore, as mentioned in angular mobility, the number of covered nodes and the time spent to cover these nodes have to be considered together. According to these results, at radius between 500m and 700m, more nodes are covered within shorter time. If we consider only the number of covered nodes, the altitude 700m is the best choice in circular mobility.

As it is seen in the Figure 4.13, altitudes affect the time spent per covered nodes. Again, the time spent per covered node is directly related with the number of covered nodes.

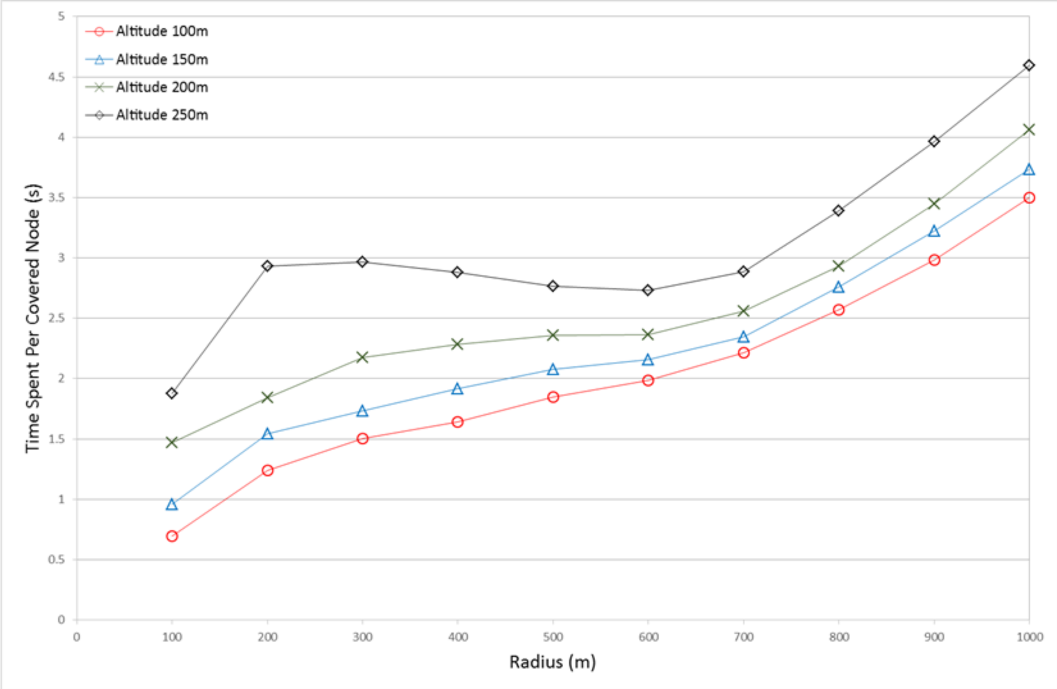


Figure 4.13 Time Spent per Covered Node in Circular Mobility

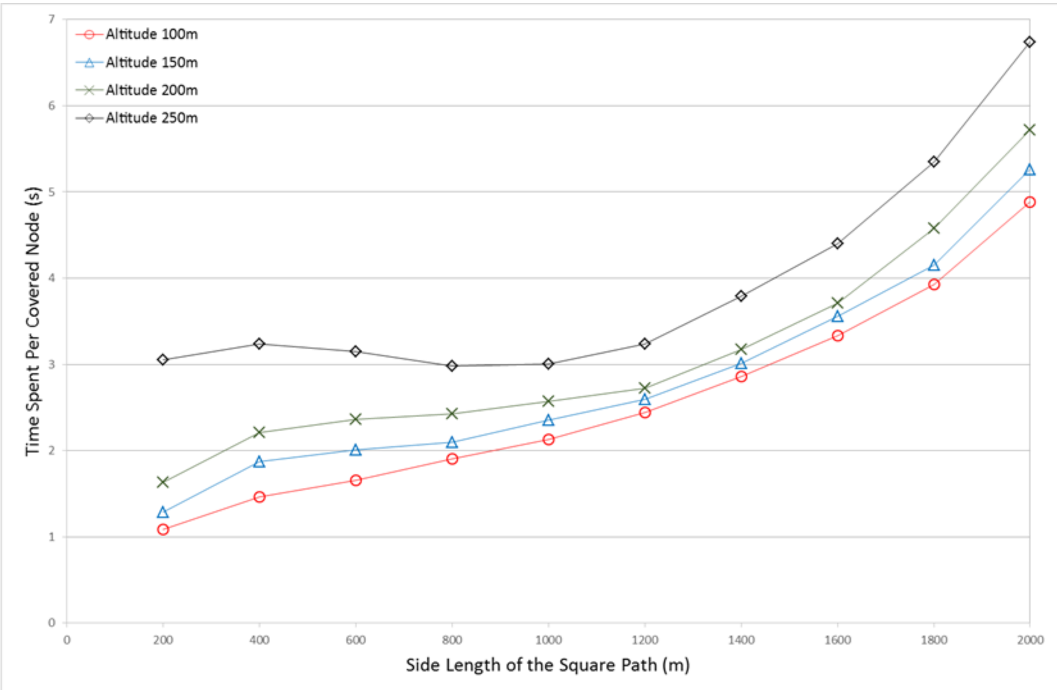


Figure 4.14 Time Spent per Covered Node in Square Mobility

Figure 4.14 shows the time spent to cover a single node in Square Mobility. As it is seen, when the side length and therefore the path length increases, the time spent to cover a single node increases slightly until length value 1200m, and then starts to increase sharply. The results for the square mobility are very similar to the results of circular mobility. We can make the same comments and evaluations for the square mobility.

Figure 4.15 shows the time spent to cover a single node in Tractor Mobility. As it is seen, when the path length decreases (the width between the tracks increases), time spent to cover a single node decreases sharply until width value 500m, and between 500m-1000m there is a moderate level decrease and after 1000m, the time spent per covered nodes starts to decreases slightly. The results for altitude 250m differ from the other altitudes. At altitude 250m, the time spent per node decreases sharply and then starts to increases again at 700m and after 1000m starts to decrease. It is totally related with the number of covered nodes.

According to these results, the time spent per covered node is very small at the width value 2000 but it is most probably an inadvisable parameter to use when the number of covered nodes is also considered.

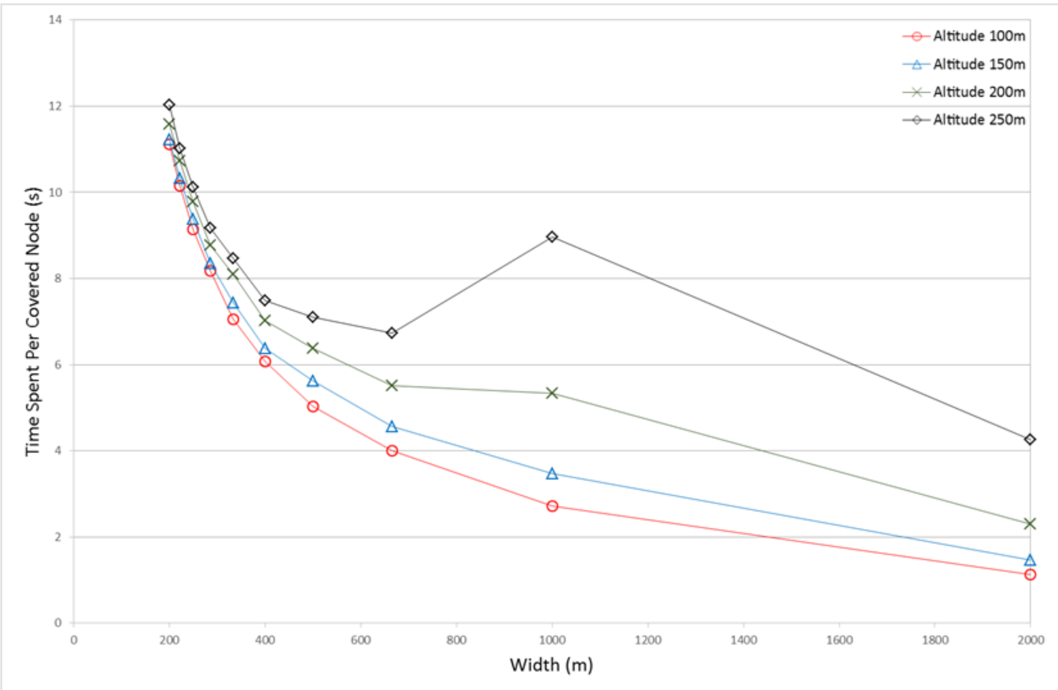
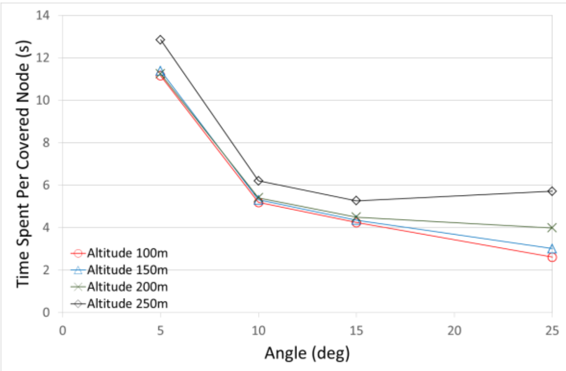
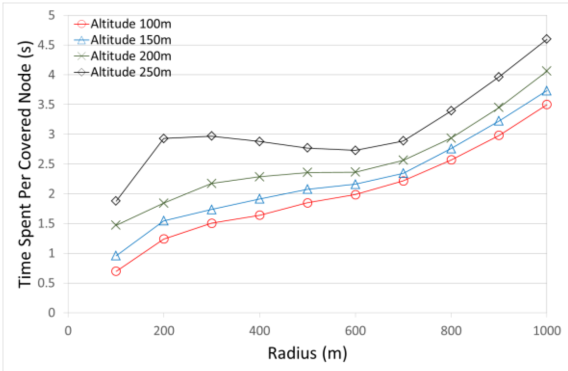


Figure 4.15 Time Spent per Covered Node in Tractor Mobility

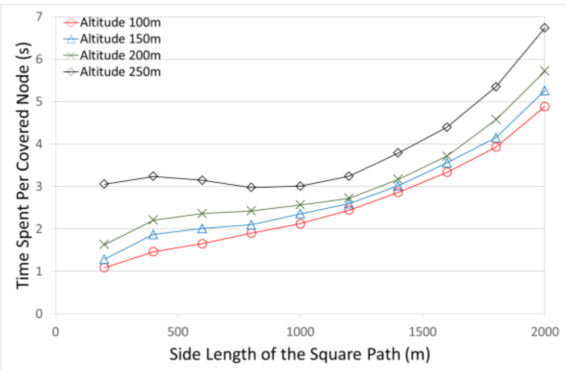
Figure 4.16 shows the time spent per covered node in all mobility patterns. It is used to show the differences clearly. In angular mobility and in tractor mobility, the time spent per covered node is very high for the some of the parameters values of angle and track width e.g. angle value 5 degree in angular mobility and track width value 200m in tractor mobility. On the other hand, depending on the parameter values, the performance metric, the time spent per covered node reduces to very small values. For these small values, it might be questionable to use these parameters in the data collection of such WSN. When we look at the number of covered nodes for the scenarios with these small values of time spent per covered node, it is seen that the values are very small meaning that very few number of nodes are covered. So, it is the network operator's responsibility to consider both metrics. It is a tradeoff whether to use the parameters with more covered nodes or the parameters with short time to cover a single node.



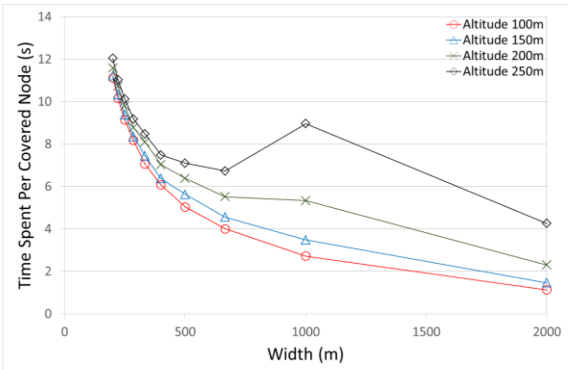
(a) Angular Mobility



(b) Circular Mobility



(c) Square Mobility



(d) Tractor Mobility

Figure 4.16 Time Spent per Covered Node in All Mobility Patterns

4.5.4. Utilization

There are many performance metrics defined to measure the performance of the system. Three of them very closer to each other. These are the utilization, the efficiency and the productivity. Corresponding formulas are given below.

$$\boldsymbol{Utilization} \quad = \frac{the\ number\ of\ covered\ nodes}{the\ number\ of\ all\ nodes} \tag{7}$$

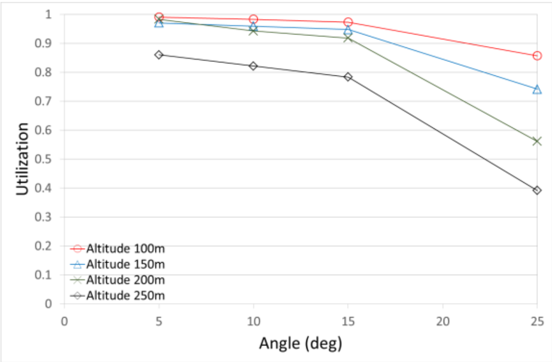
$$\boldsymbol{Efficiency} \quad = \frac{the\ number\ of\ covered\ nodes\ (in\ that\ scenario)}{max.\ number\ of\ covered\ nodes\ (in\ all\ scenarios)} \tag{8}$$

$$\boldsymbol{Productivity} = \frac{the\ number\ of\ covered\ nodes}{the\ the\ time\ UAV\ spent\ in\ the\ operation\ area} \tag{9}$$

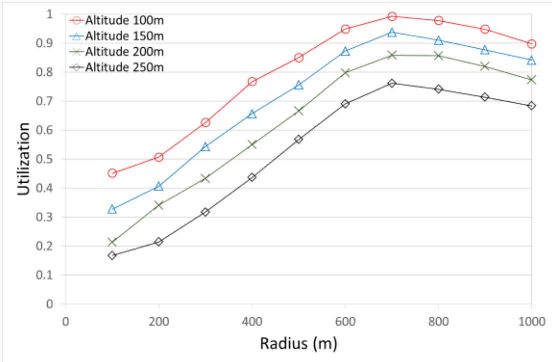
Productivity (9) is the inverse of the performance metric "*the time spent to cover a single node*" (6). Therefore, the results for the productivity will not be given because we have already given the results for the time spent per covered node.

The utilization (7) and the efficiency (8) are very close to each other giving almost similar results and the same curve pattern in the graphs. Their *y*-scales range between 0-1. Therefore rather than using both metrics, we have used only utilization in the evaluations. Previously, the results for the performance metric "the number of covered nodes" were presented. It is clear that the utility metric is the normalization of "*the number of covered nodes*" where the utility value varies between 0 and 1. Therefore, rather than presenting each graph in separate figures, we present utility performance graphs of the mobility patterns in a single figure. Figure 4.17 presents the utility results for all mobility patterns. The graphs presented in "the number of covered nodes" can be referred in need of more detailed information on each graph.

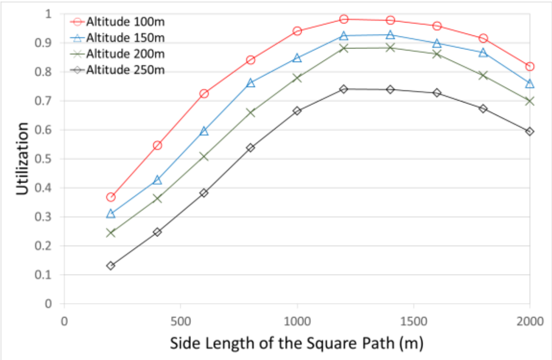
The utilization graphs of circular mobility and square mobility are very similar to each other. When the circle or the square size is small, the utilization is also low. As the size of the circle and the square grows, the utilization increases. However, in both mobility patterns, after a peak value, the utilization starts to decrease. The reason is about the gaps beginning to grow in the center of the circle and the square. These cases and their effects are explained in the section for the performance metric, the number of covered nodes.



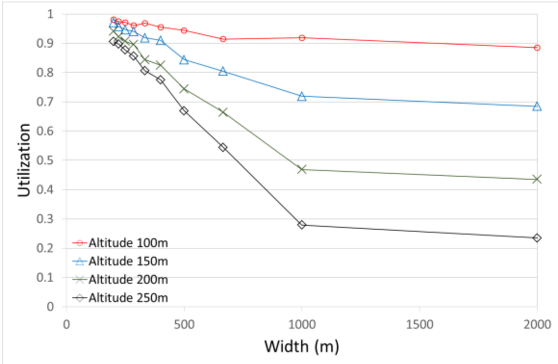
(a) Angular Mobility



(b) Circular Mobility



(c) Square Mobility



(d) Tractor Mobility

Figure 4.17 Utilization in All Mobility Patterns

In the angular mobility, the utilization is very high when the angle value is small for all altitude values. For the altitude 100m, the utilization is decreasing slightly but is very high compared to the other altitudes. In other altitudes, the utility decreases slightly until angle value 15 degrees and decreases more at the angle value 25 degrees. Altitude 250m has the worst utilization results. It is seen in this graph that the altitude and the angle value affect the utilization. Small angle value and lower altitudes increase the connectivity and accessibility to the UAV.

Tractor mobility performs similar to the angular mobility. For the UAV altitude 100m, it performs better than other altitudes and the utilization decreases slightly even the width between tracks increases. However, other altitudes are affected much from the increase in the width of the tracks and the utilization decreases sharply as the width and altitude increases.

4.5.5. Time and Coverage Efficiency

In the metrics presented above, it is seen that considering only the coverage of the nodes or the time elapsed to cover the nodes are not enough and may lead to take false decisions. While maximizing the number of nodes is an important metric, minimizing the elapsed time is another important metric. The UAV flying over the operation area may not have enough energy to complete its mission. Or, the UAV may have limited time to collect the necessary data as much as possible. Therefore, time and coverage metrics have to be analyzed together

In this thesis, we define a new metric which is a measure of the time and coverage. It is named as Time-Coverage Efficiency. The aim is maximizing the number of covered nodes while minimizing the number of operation time. In other words, time spent for a node has to be minimized while maximizing the number of covered nodes. The equation for this new metric is given below:

$$Time - Coverage\ Efficiency = maximize\ (num.of\ covered\ nodes)\ x\ minimize(time\ spent\ per\ covered\ node) \quad (10)$$

$$Time - Coverage\ Efficiency \sim \frac{number\ of\ covered\ nodes}{time\ spent\ per\ covered\ node} \quad (11)$$

$$Time - Coverage\ Efficiency = \frac{(number\ of\ covered\ nodes)^2}{(time\ spent\ per\ covered\ node)^{\frac{1}{2}}} \quad (12)$$

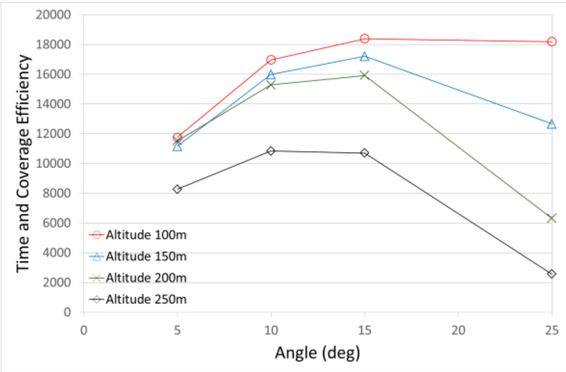
In (12), the square of the number of covered nodes is used in the numerator and the square root of the time spent per covered node is used in the denominator of the fraction. We take the square of the number of covered nodes because it must be promoted to higher values as much as possible. On the other hand, the time spent per covered node has to be minimized as much as possible. In the evaluation and comparison, scenarios which perform better in terms of these metrics, more number of covered nodes and less time spent per covered node, have to be identified and be recommended to be used in the operation area. Therefore, we defined the metric as given in (12).

Figure 4.18 shows the Time and Coverage Efficiency in all mobility patterns. In angular mobility pattern, it is seen that although more nodes are covered with the angle value 5 at all altitudes, it is not the most efficient one due to the duration it takes to sweep the operation area. With angle 5, more legs are constructed which increase the total length of the UAV path. This leads to cover more nodes but in longer duration. However, as the angle increases, the number of legs decreases, which eventually decreases the path length of the UAV. It takes less time to sweep the area. On the other, when the number of covered nodes is considered, there is slight decrease. It means that as a tradeoff letting only a few nodes uncovered, the UAV saves time to collect data. This is true for angle degree 10 and 15. For angle 25, although the UAV has the minimum flight path, there is a sharp decrease in the number of covered nodes, especially for altitude 250m. When the figure of angular mobility is considered, angle 15 presents the optimistic results for time-coverage efficiency. It is also seen that the performance of the altitude 250 is the worst among the others, and the angle 10 present better results than the angle 15 degrees.

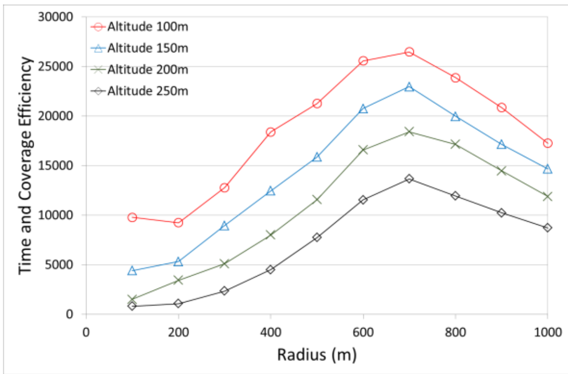
In circular mobility, it is clearly seen that circular mobility pattern with the radius 700m is better than other radius values in all altitudes. It can also be verified by looking at the metrics, the number of covered nodes and the time spent per node graphs.

In square mobility, very similar to the circular mobility, it is clearly seen that square mobility pattern with the side length 1200m is better than other side length values in all altitudes. This information can also be verified by looking at the metrics, the number of covered nodes and the time spent per node graphs.

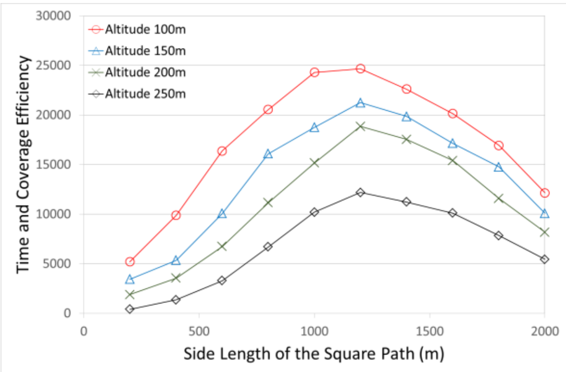
The performance of the tractor mobility is very different compared to the other mobility patterns. For the 100m altitude, as the width between tracks gets larger, time-coverage efficiency increases. The reason is related with the reduced flight time of the UAV by decreasing the path while preserving the number of covered nodes stable. However, the situation is very different at other altitudes. As the width increases, the time-coverage efficiency value follows a stable pattern for the 150m altitude and decreases sharply for 200m and 250m altitudes. Altitude 250 performance is very poor compared to the others.



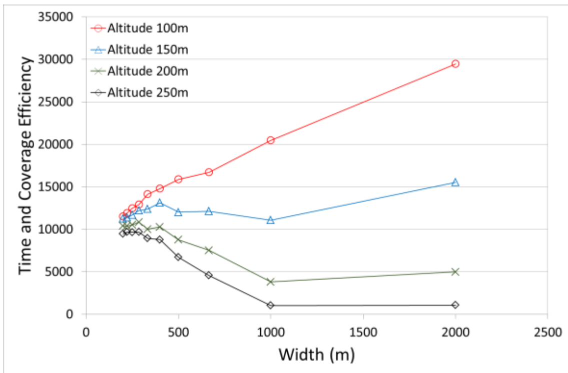
(a) Angular Mobility



(b) Circular Mobility



(c) Square Mobility



(d) Tractor Mobility

Figure 4.18 Time and Coverage Efficiency in All Mobility Patterns

In all mobility patterns, the UAV altitude 100m performs better than other altitude values. The reasons are explained previously and illustrated in Figure 3.2 and Figure 3.3. However, for a specific mobility pattern, the depending on the altitude the most appropriate performance parameter that presents the highest results may differ. For example, in the angular mobility, the most appropriate angle value for the best performance is 10 degree for the altitude 250m where the most appropriate angle value for the best performance is 15 degree for the altitude 200m. Depending on the operation altitude of the UAV and mobility pattern, the operator can select the parameter to get better performance results.

4.5.6. Normalized Time and Coverage Efficiency

Although the time-coverage efficiency metric provides many valuable information, it is necessary to normalize the results to allow them be compared with each other. Equation

(4) represents the efficient of normalized time and efficient of normalized coverage of each mobility pattern.

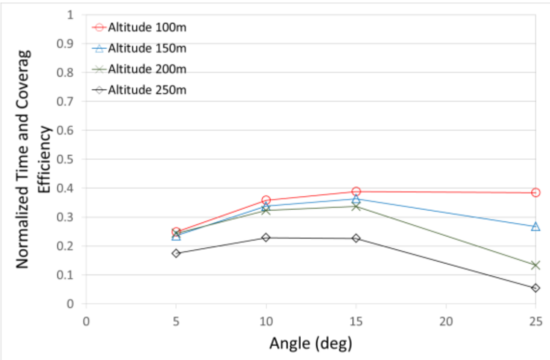
$$Normalized\ Time - Coverage\ Efficiency = \left[\frac{\left(\frac{number\ of\ covered\ nodes}{\max\limits_{all\ scenrios} (number\ of\ covered\ nodes)} \right)^2}{\left(\frac{time\ spent\ per\ covered\ node}{\min\limits_{all\ scenarios} (time\ spent\ per\ covered\ node)} \right)^{\frac{1}{2}}} \right] \quad (13)$$

Equation (13) is similar to (12) where numerator and the denominator are divided by new values. Numerator is divided by the maximum number of covered nodes among all scenarios including all mobility patterns and altitudes to normalize this value between 0 and 1. Similarly, the denominator “time spent per covered node” is divided by the minimum time spent per covered node nodes among all scenarios including all mobility patterns and altitudes to normalize this value. There will be a value between 0 and 1 to let the results be compared in the same scale.

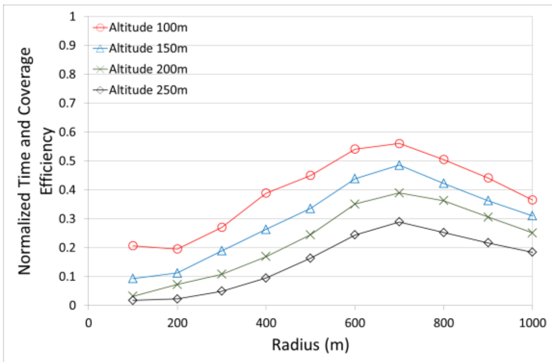
Figure 4.19 shows the Normalized Time and Coverage Efficiency in all mobility patterns. It reveals the details and the hidden points in the comparison. With a one shot view, the differences are clearly seen. For example, although the results of circular mobility and the square mobility are similar to each other where the curves present similar patterns, there are differences in the performance. The curve pattern similarity is seen in the number of covered nodes graphs. However, we are not able to see the difference and its magnitude in those graphs. However, with the use of Figure 4.19, are able to see the differences and their magnitudes. Hence, more accurate decisions can be given by decision maker e.g. UAV operators.

When the graphs are compared with each other, it is seen that, generally, the circle mobility and square mobility have superiority over the others, where the circle mobility is the most superior one. The tractor mobility performs better only at the altitude 100m. in other altitudes it doesn’t perform well compared to the others due to the increases path length and operation duration in the tractor mobility.

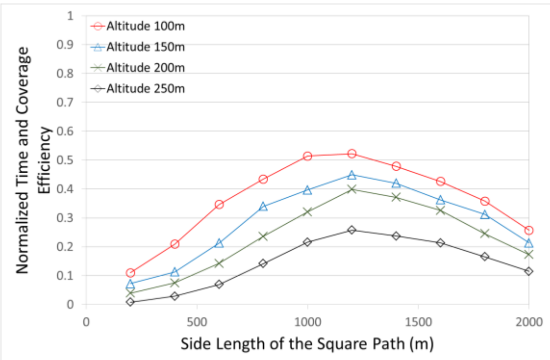
On the other, the graphs in Figure 4.19 are very useful to compare the performance of the mobility patterns at each altitude. For example, the question could be “which mobility patterns perform better and at what parameter values for the UAV altitude value 100m?” The answer will be the tractor mobility with width value 2000m (a single track). However, the UAVs may not fly at this altitude at every area or zone. For the same question, if the altitude is increased to 150m, then the circle mobility has to be selected with the radius of 700m. If the altitude is increased to 200m, either the square mobility with the side length 1200m or the circular mobility with the radius 700m can be selected.



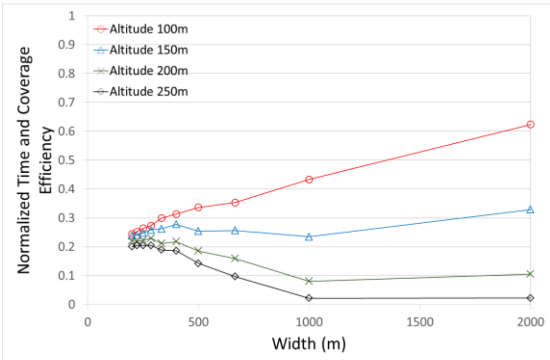
(a) Angle Mobility



(b) Circle Mobility



(c) Square Mobility



(d) Tractor Mobility

Figure 4.19 Normalized Time and Coverage Efficiency in All Mobility Patterns

If only two mobility patterns are considered e.g. angle mobility and tractor mobility, for some altitudes angular mobility performs better and for the other altitudes the tractor mobility performs better.

As it is seen, each mobility patterns presents different performance results. In making decision to select the best appropriate mobility pattern to be applied in the operation area, there could be two main objectives, first covering the maximum nodes, second, spending less amount of time in the operation area with maximum utilization. By defining the Time-Coverage Efficiency metric, we address this problem by finding the most appropriate mobility pattern with the best performance results.

CONCLUSIONS

Using UAV as mobile sink is one of the best and efficient way to provide better coverage and connectivity for all nodes that are deployed in a large scale operation area. The coverage depends on some fixed operational parameters of the UAV such as speed and altitude. Also, considering the UAV path for the cluster formation in WSN is important to increase the coverage/connectivity. If a well-defined clustering algorithm is used in the WSN, then we can change the path of the UAV according to our needs.

In this research, the mobility patterns and their effects on the performance has been explored. It is seen that depending on the mobility pattern, the number of the clusters and the number of accessed sensor nodes varies. Another research question is related with the operation time. The operation time of the UAV can be costly or the UAV can be incapable to complete the mission due to the time limitations. The solution is covering as many nodes as possible within a shorter period of time. Therefore, there is a tradeoff between the operation time of the UAV and the covered (accessed) nodes. The best appropriate approach can be selected considering the main objective of the WSN and the operation of UAV. We address this problem and present the results for the tested scenarios. Studies are evaluated with OMNET++ which provides realistic environment, in which realistic MAC and PHY layers and real path loss values are used with help of MIXIM framework. This study in this thesis contributes to enhance the coverage and connectivity in large scale wireless sensor networks (WSNs). It is one of the first studies that consider the effect of different mobility patterns using mobile sink in cluster formation.

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RESUME

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EDUCATION

M.S., Computer Engineering Marmara University, Faculty of Engineering, Istanbul, Turkey, 2015

Thesis Topic: Effects of UAV Mobility Patterns on Data Collection in Wireless Sensor Networks, *Advisor*: Asst. Prof. Müjdat SOYTÜRK.

B.S., Computer Engineering University of Mosul, Mosul, Iraq, 2008.

WORK EXPERIENCE

2012 *Supervisor*, Delta Company, Mosul, Iraq.

2011 *Manager of Wireless Network Group*, Nineveh Governorate, Mosul, Iraq.

2010 *Manager of Maintenance Group*, Nineveh Governorate, Mosul, Iraq.

QUALIFICATIONS

Certified Cisco Networking Academy (CCNA).

Certified Wireless Training Course.

Certified Personal Strategic Planning (PSP).

C/C++ Programming Language.

JAVA Programming Language

Have a good knowledge in WIFI and WiMAX Networks for Internet.

Have a good knowledge in programming (Routers and Switches).

PROFESSIONAL SKILLS

TOEFL IBT (2012): Listening: C2 Reading: C2 Writing: C1 Speaking: C1 Overall Band Score: 82

Using Ubuntu Linux as developing environment.

Effective Use of different platforms (Linux and Windows) and with several IDEs (Eclipse and NetBeans).

PUBLICATIONS

Sarmad Rashed, Mujdat Soyturk. “Effects of UAV Mobility Patterns on Data Collection in Wireless Sensor Networks”, IEEE International Conference on Communication, Networks and Satellite, IEEE COMNETSAT'2015, Dec. 2015.

RESEARCH INTERESTS

Wireless Sensor Networks, Networks and Security.

RESEARCH PROJECTS

Effects of UAV Mobility Patterns on Data Collection in Wireless Sensor Networks.

Programming serial EEPROM using serial port.

MOTHER LANGUAGE

Arabic

FOREIGN LANGUAGES

English (fluent)

Turkish (Very Good)

AWARDS AND HONORS

B.Sc. Graduation 10^{th} among 30 graduates.

M.Sc. Turkish Government Scholarship.