**MAKERERE UNIVERSITY**

**COLLEGE OF ENGINEERING, DESIGN, ART, AND TECHNOLOGY**

**SCHOOL OF ENGINEERING**

**DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING**

# OPTIMAL PLACEMENT OF UNMANNED AERIAL VEHICLE BASE STATIONS

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December 15, 2020

*Undergraduate thesis Submitted in Partial Fulfilment of the award of the Degree of Bachelor of Science in Telecommunications Engineering of Makerere University*

# Declaration

I, **NSAMBA KATO ARUSHAD** hereby declare that the information in this report is a true compilation of my original work and has not been submitted to any college, university, or institution for any academic award.

Signature: ........................................    Date: ...15 /12 /2022...

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We, the supervisors, have approved this dissertation. it meets the examiners' requirement for the Bachelor of Science in Telecommunications Engineering Degree of Makerere University.

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# Dedication

I dedicate this report to my parents, guardians, relatives, and my friends for their love, care, and support towards my successful academic journey.

# Acknowledgment

First and importantly, I thank the Almighty GOD for his gracious mercy, protection, good health, and for all his other provisions that have enabled me to come to the end of this Degree and the completion of this report.

I would also like to extend my sincere gratitude to my main supervisor, Dr.Hanifa Nabuuma for her guidance and great support throughout this entire project period. Her boundless energy, strong devotion, and continuous encouragement to my project have been truly remarkable may the sovereign Lord richly bless and reward her.

In the same respect, I thank Mr. Derrick Sebbaale my Co-Supervisor for the endless support and help during my project work am forever grateful and so much humbled.

Let me also thank my brother Kabona Ali my project partner for his tremendous and tireless collaboration towards the success of our project and also for making the project period such a good and enjoyable academic experience.

With a great deal of gratitude, I take this opportunity to thank my lovely parents and family for their endless support both financially and for nurturing me to be fit and easily absorbed by society as a whole may the LORD reward you abundantly.

# Abstract

The optimal placement of multiple unmanned aerial vehicles (UAVs) equipped with directional antennas acting as wireless base stations that provide coverage to several ground users is analyzed.

In this research, the optimal placement of unmanned aerial base stations that provide coverage for the ground terminals (users) is analyzed and uses the case study of an MTN malfunctioning terrestrial base station where UAVs are deployed to give coverage to the ground users as the base station problem is being rectified by the maintenance MTN engineers

First, the downlink coverage probability as a function of altitude and antenna gain is derived based on the probabilistic line of sight or non-line of sight links (Los/NLoS) links. Next, using circle packing theory, the 3-D locations of the UAVs are determined in the way that the total coverage area is maximized while maximizing the coverage lifetime of the UAVs.

Given a desired geographical area that needs to be covered by multiple UAVs, an efficient deployment approach is proposed based on the circle packing theory that leads to maximum coverage while each UAV uses a minimum transit power.

The results show that the optimal altitude and locations of the UAVs can be determined based on the number of available UAVs, the antenna gain, and beamwidth.

Results also show that to mitigate interference, the altitude of the UAVs must be properly adjusted based on the beamwidth of the directional antenna as well as the coverage requirements.

Furthermore, the minimum number of UAVs required to guarantee a target coverage probability for a given area is determined.

## Table of Contents

# List of figures

# List of tables

# List of acronyms

| | |
|---|---|
| UAV | Unmanned aerial vehicles |
| BSc | Base station UEs |
| User equipment LoS | |
| Line of sight NLoS | |
| Non line of sight | |
| IoT | Internet of Things |
| QoS | Quality of Service |
| HAP | High Altitude Platforms |
| LAP | Low Altitude Platforms |
| D2D | Device to Device communication |
| SBSs | Small Base Stations |
| MBSs | Mobile Base Stations |
| GTs | Ground Terminals |
| GDC | Geometric Disk Cover |
| FSPL | Free Space Path loss |

# Chapter 1

## 1 Introduction

This chapter introduces the project background, problem statement, justification, project objectives, scope, and the thesis outline

### 1.1 Project background

The use of unmanned aerial vehicles (UAVs) that act as flying base stations is seen as a promising approach to enhance the coverage and rate performance of wireless networks in different scenarios such as temporary hot spots and emergencies having malfunction terrestrial base stations such as floods, landslides among others. For example, mobile UAVs can establish efficient communication links to deliver messages to ground users, such as sensors [1]

Also, the agility and resilience requirements of future cellular networks may not be fully satisfied by terrestrial base stations in cases of unexpected or temporary events. A promising solution is assisting the cellular network via low-altitude unmanned aerial vehicles equipped with base stations, i.e., drone-cells. Although drone-cells provide a quick deployment opportunity as aerial base stations, efficient placement becomes one of the key issues [2].

In addition to mobility of the drone-cells in the vertical dimension as well as the horizontal dimension, the differences between the air-to-ground and terrestrial channels cause the placement of the drone-cells to diverge from the placement of terrestrial base stations [2].

Next generation cellular networks have high reliability and availability demands. Be it a natural disaster, extreme densities of users in an area, or providing connectivity in rural areas, the cellular network needs to meet certain quality of service (QoS) requirements. However, these situations are either unexpected or temporary. As a result, it is not feasible to invest in an infrastructure that will provide revenue for a relatively short time. A potential solution to these problems is assisting the cellular network via low-altitude unmanned aerial vehicles (UAV) that can serve as aerial base stations with a quick deployment opportunity, i.e. drone-cells [2].

Indeed, using UAVs as aerial base stations provides several advantages. First, due to their higher altitude, aerial base stations have a higher chance of line-of-sight (LoS) links to ground users. Second, UAVs can easily move and have a flexible deployment, and hence, they can provide rapid, on-demand communications

However, one of the biggest challenges is to determine the optimal placement of the drone-cell so that the network can benefit [2]. One must overcome many technical challenges. These challenges include the optimal 3D deployment of UAVs, energy limitations, interference management, and path planning. In particular, the deployment problem is of paramount importance as it highly impacts energy consumption as well as the interference generated by UAVs [1].

## 1.2 Problem statement

Due to the occurrence of emergencies scenarios such as floods, landslides, road constructions that damage telecommunication infrastructure disrupting telecommunication services among others leading to the malfunction of terrestrial base stations, UAVs are deployed to provide temporary coverage or to act as temporary hot spots to several users in that specific area before the terrestrial base station can be fixed since the installation of a terrestrial base station takes a lot more time, or used in offloading overcrowded terrestrial base stations such as stadiums during events. Therefore, deployment of UAVs to provide temporary coverage to such areas and no significant infrastructure is required and it is fast and flexible [1].

It is also expensive in terms of capital expenditure and operating cost in terrestrial base stations and it cost a lot of dollars compared to UAVs deployment. Deploying UAVs as the base station doesn’t require a lot of expenses. UAVs are a practical solution in emergency and disaster relief scenarios. This is critical when the terrestrial network is down [2].

## 1.3 Justification

With their maneuverability and increasing affordability, unmanned aerial vehicles (UAVs) have many potential applications in wireless communication systems. In particular, UAV mounted mobile base stations (MBSs) can be deployed to provide wireless connectivity in areas without infrastructure coverage such as battlefields or disaster scenes such as landslides in Bududa eastern Uganda. Unlike terrestrial base stations (BSs), even those mounted on ground vehicles, UAV-mounted MBSs can be deployed in any location and move along any trajectory constrained only by their aeronautical characteristics, to cover the ground terminals (GTs) in a given area based on their known locations [3]. Therefore, an efficient deployment method that leads to maximum coverage performance while ensuring or meeting other coverage constraints is proposed.

In Uganda’s context, the country aspires to transform the agriculture sector from subsistence farming to commercial agriculture. This will make agriculture profitable, competitive, and sustainable to provide food and income security to all the people of Uganda. It will also create employment opportunities along the entire commodity value chain of production, processing, and marketing. As a way of increasing agricultural productivity, the government will ensure continued investment in technology improvement; drones are likely to be used by farmers to spray crops with pesticides. Besides agricultural sector transformation, the police are likely to use drones as crime surveillance, Uganda Electricity Transmission Company Limited engineers sensed that their M600 drone was going to be fully utilized to address the challenge of managing electricity transmission line. In the information communication technology future prospective, we predict that drones will be highly utilized in Uganda’s vision 2040. There will be a lot to do with drones hence increasing their numbers. This means that if drones are not planned for, there will be a lot of interferences in wireless communications [4].

## 1.4 Project objectives

### 1.4.1 Main Objective

- To minimize the number of UAVs that can be deployed to provide coverage to a given area.

### 1.4.2 Specific objectives

- To model a network of UAVs
- To develop an optimization algorithm for the placement of UAVs while meeting coverage constraints.
- To analyze the performance of the algorithm and compare it with existing algorithms.

## 1.5 Scope

In this project first, the downlink coverage probability for the UAVs as a function of the altitude and the antenna gain is derived. Next, using circle packing theory, the 3-D locations of UAV are determined in a way that total coverage area and coverage lifetime are both maximized. To mitigate interference, the altitude of the UAVs is properly adjusted basing on the beamwidth of directional antennas and coverage requirements. Thereafter the minimum number of UAVs needed to guarantee a target coverage probability for a given geographical area is determined.

## 1.6 Thesis outline

This thesis consists of five chapters as below.

Chapter 1 consists of the project background, the problem statement, justification, objectives, and the scope.

Chapter 2 consists of the brief literature as regards the concepts behind an introduction to UAVs, cellular networks, shadow fading, radio interference, circle packing, probability of line of sight in urban environments, and three-dimension placement of UAVs for congestion mitigation.

Chapter 3 consists of the methodology including; tools, system model, channel models, problem formulation, and simulation parameters.

Chapter 4 consists of the simulation results and performance analysis for the results obtained.

Chapter 5 consists of the challenges, recommendations, and conclusions during the implementation of the project.

# Chapter 2

## 2 Literature Review

This chapter discusses an introduction to UAVs, cellular networks, shadow fading, radio interference, circle packing, probability of line of sight in urban environments, and three-dimension placement of UAVs for congestion mitigation.

## 2.1 Introduction on UAVs

Unmanned aerial vehicles (UAVs), commonly known as drones, have been the subject of concerted research over the past few years, owing to their autonomy, flexibility, and a broad range of application domains. Indeed, UAVs have been considered as enablers of various applications that include military, surveillance and monitoring, telecommunications, delivery of medical supplies, and rescue operations, and. However, such conventional UAV-centric research has typically focused on issues of navigation, control, and autonomy, as the motivating applications were typically robotics or military-oriented. In contrast, the communication challenges of UAVs have typically been either neglected or considered as part of the control and autonomy components [5].

### 2.1.1 Motivation

The unprecedented recent advances in drone technology make it possible to widely deploy UAVs, such as drones, small aircraft, balloons, and airships for wireless communication purposes. In particular, if properly deployed and operated, UAVs can provide reliable and cost-effective wireless communication solutions for a variety of real-world scenarios. On the one hand, drones can be used as aerial base stations (BSs) that can deliver reliable, cost-effective, and on-demand wireless communications to desired areas. On the other hand, drones can function as aerial user equipments (UEs), known as cellular-connected UAVs, in coexistence with ground users (e.g., delivery or surveillance drones). This exciting new avenue for the use of UAVs warrants a rethinking of the research challenges with wireless communications and networking being the primary focus, as opposed to control and navigation [5].

In particular, when UAVs are used as flying, aerial base stations, they can support the connectivity of existing terrestrial wireless networks such as cellular and broadband networks. Compared to conventional, terrestrial base stations, the advantage of using UAVs as flying base stations is their ability to adjust their altitude, avoid obstacles, and enhance the likelihood of establishing line-of-sight (LoS) communication links to ground users. Indeed, owing to their inherent attributes such as mobility, flexibility, and adaptive altitude, UAV base stations can effectively complement existing cellular systems by providing additional capacity to hotspot areas and by delivering network coverage in hard to reach rural areas. Another important application of UAVs is in the Internet of Things (IoT) scenarios whose devices often have small transmit power and may not be able to communicate over long ranges. UAVs can also serve as wireless relays for improving connectivity and coverage of ground wireless devices and can also be used for surveillance scenarios, a key use case for the IoT. Last, but not least, in regions or countries where building a complete cellular infrastructure is expensive, deploying UAVs becomes highly beneficial as it removes the need for expensive towers and infrastructure deployment.

From an industry perspective, key real-world examples of recent projects that employ drones for wireless connectivity include Google's Loon project. Within the scope of these practical deployments, UAVs are being used to deliver Internet access to developing countries and provide airborne global Internet connectivity. Moreover, Qualcomm and AT&T are planning to deploy UAVs for enabling wide-scale wireless communications in the upcoming fifth-generation (5G) wireless networks Meanwhile, Amazon Prime Air and Google's Project Wing initiatives are prominent examples of use cases for cellular-connected UAVs [5].

Despite such promising opportunities for drones, one must address many technical challenges to effectively use them for each specific networking application. For instance, while using drone-BS, the key design considerations include performance characterization, optimal 3D deployment of drones, wireless and computational resource allocation, flight time and trajectory optimization, and network planning. Meanwhile, in the drone-UE scenario, handover management, channel modeling, low-latency control, 3D localization, and interference management are among the main challenges [5].

### 2.1.2 UAV Classification

Naturally, depending on the application and goals, one needs to use an appropriate type of UAV that can meet various requirements imposed by the desired quality-of-service (QoS), the nature of the environment, and federal regulations. To properly use UAVs for any specific wireless networking application, several factors such as the UAVs' capabilities and their flying altitudes must be taken into account. In general, UAVs can be categorized, based on their altitudes, into high altitude platforms (HAPs) and low altitude platforms (LAPs). HAPs have altitudes above 17km and are typically quasi-stationary. LAPs, on the other hand, can fly at altitudes of tens of meters up to a few kilometers, can quickly move, and are flexible [5].

We note that, according to US Federal aviation regulations, the maximum allowable altitude of LAP-drones that can freely fly without any permit is 400 feet. Compared to HAPs, the deployment of LAPs can be done more rapidly thus making them more appropriate for time-sensitive applications (e.g., emergencies). Unlike HAPs, LAPs can be used for data collection from ground sensors. Moreover, LAPs can be readily recharged or replaced if needed. In contrast, HAPs have longer endurance and they are designed for long term (e.g., up to few months) operations. Furthermore, HAP systems are typically preferred for providing and wide-scale wireless coverage for large geographic areas. However, HAPs are costly and their deployment time is significantly longer than LAPs [5].

UAVs can also be categorized, based on type, into fixed-wing and rotary-wing UAVs. Compared to rotary-wing UAVs, fixed-wing UAVs such as small aircraft have more weights, higher speed, and they need to move forward to remain aloft. In contrast, rotary-wing UAVs such as quadrotor drones, can hover and remain stationary over a given area [5].

### 2.1.3 UAV Regulations

Regulatory issues are important limiting factors facing the deployment of UAV-based communication systems. Despite the promising applications of UAVs in wireless networks, there are several concerns regarding privacy, public safety, security, collision avoidance, and data protection. In this regard, UAV regulations are being continuously developed to control the operations of UAVs while considering various factors such as UAV type, spectrum, altitude, and speed of UAVs. In general, five main criteria are often considered when developing UAV regulations. Applicability: pertains to determining the scope (considering type, weight, and role of UAVs) where UAV regulations are applied, Operational limitations: related to restrictions on the locations of UAVs, Administrative procedures: specific legal procedures could be needed to operate a UAV, Technical requirements: includes communications, control, and mechanical capabilities of drones, Implementation of ethical constraints: related to privacy protection [5].

### 2.1.4 Challenges:

The three-dimensional deployment of UAVs is one of the key challenges in UAV-based communications. The adjustable height of UAVs and their potential mobility provide additional degrees of freedom for efficient deployment. As a result, optimal deployment of UAVs has received significant attention in fact, deployment is a key design consideration while using UAVs for coverage and capacity maximization, public safety, smart cities, caching, and IoT applications. The optimal 3D placement of UAVs is a challenging task as it depends on many factors such as deployment environment (e.g., geographical area), locations of ground users, and UAV-to-ground channel characteristics which itself is a function of a UAV's altitude. Besides, simultaneously deploying multiple UAVs becomes more challenging due to the impact of inter-cell interference on the system performance. The deployment of UAVs is significantly more challenging than that of ground base stations, as done in conventional cellular network planning. Unlike terrestrial base stations UAVs need to be deployed in a continuous 3D space while considering the impact of altitude on the A2G channel characteristics. Moreover, while deploying UAVs, their flight time and energy constraints must be also taken into account, as they directly impact the network performance [5].

## 2.2 Cellular Networks

Cellular networks use multiple low-power transmitters (100 W or less) Areas divided into cells Each served by its antenna Served by base station consisting of transmitter, receiver, and control unit Band of frequencies allocated Cells set up such that antennas of all neighbors are equidistant (hexagonal pattern)

### 2.2.1 Frequency Reuse

Adjacent cells are assigned different frequencies to avoid interference or crosstalk.

The objective is to reuse frequency in nearby cells 10 to 50 frequencies assigned to each cell. Transmission power controlled to limit power at that frequency escaping to adjacent cells. The issue is to determine how many cells must intervene between two cells using the same frequency [6].

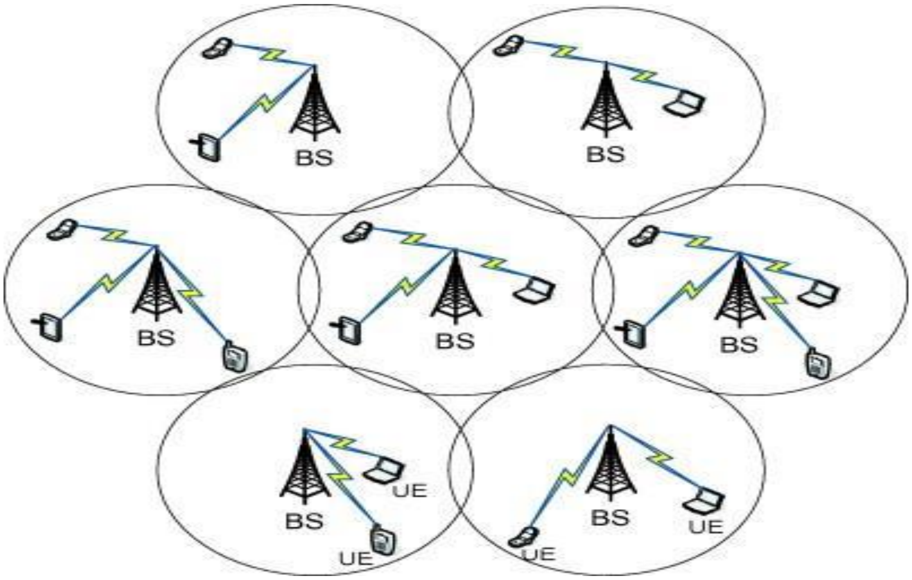

Figure 2.1:Figure showing a cellular communication network *[6]*.

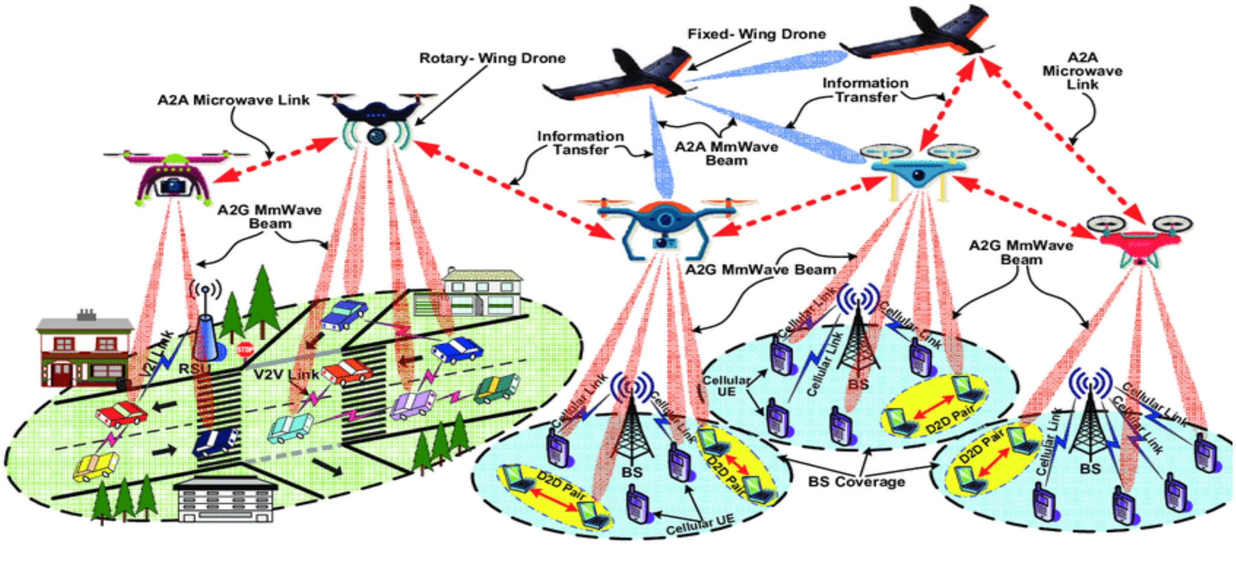

Figure 2.2:Figure showing a UAV wireless network *[7]*.

### 2.2.2 Antenna Radiation Pattern

An antenna radiation pattern (or antenna pattern) is defined as a mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates, defined for the far-field, Expressed as a function of directional coordinates, There can be field patterns (magnitude of the electric or magnetic field) or power patterns (square of the magnitude of the electric or magnetic field), Often normalized to their maximum value, The power pattern is usually expressed in decibels (dB). A radiation lobe is a portion of the radiation pattern intersected by regions of relatively weak radiation intensity. The pattern consists of main lobes, minor lobes, side lobes, and back lobes. Minor lobes usually represent radiation in undesired directions and should be minimized. Side lobes are normally the largest of the minor lobes. The level of minor lobes is usually expressed as a ratio of the power density, often termed as the side lobe ratio or side lobe level (SLL) [8].

### 2.2.3 Antenna Beamwidth

Beamwidth is the aperture angle from where most of the power is radiated. The two main considerations of this beamwidth are Half Power Beam Width (HPBW) and First Null Beam Width (FNBW).

Half-Power Beam Width

According to the standard definition, "The angular separation, in which the magnitude of the radiation pattern decreases by 50% (or -3dB) from the peak of the main beam, is the Half Power Beam Width." In other words, Beamwidth is the area where most of the power is radiated, which is the peak power. Half power beamwidth is the angle at which relative power is more than 50% of the peak power, in the effective radiated field of the antenna [9].

Indication of HPBW

When a line is drawn between the radiation pattern's origin and the half-power points on the major lobe, on both sides, the angle between those two vectors is termed as HPBW, half-power beamwidth.

Mathematical Expression

The mathematical expression for half-power beamwidth is :

Half power Beam width=70λ/D

Where λ is the wavelength (λ = 0.3/frequency), **D** is Diameter. The unit of HPBW is radians or degrees [9]

### 2.2.4 Power

One of the radio propagation concepts is the concept of power. In physics, it refers to the amount of energy consumed per unit of time. There are various units of measuring power: the joule per second, the watt, the horsepower, etc.

In radio, microwave and fiber-optic networks the unit of measure of power is the Decibel-milliwatt (dBm). The dBm is an electrical power unit in decibels (dB) referenced to 1 milliwatt (mW).

Here is the formula for representing the power in dBm:

$P_{(dBm)} = 10 \cdot \log_{10}(P_{(mW)} / 1mW)$

The transmit power (Tx) is the energy transmitted through a specific bandwidth, generated by the radio into the Radio Frequency (RF). Tx power is typically measured in dBm or W.

The received power (Rx) is the energy of the received signal and is also measured in dBm

The relationship between the transmitted power $\boldsymbol{P_t}$ and the received power $\boldsymbol{P_r}$ is given by:

$$P_r = P_t G_t G_r (4\lambda\pi d)^2 \qquad (1)$$

Where,

$G_t$ is the transmitter antenna gain
$G_r$ is the receiver antenna gain
d is the distance between the transmitter and receiver

λ is the wavelength of the signal

### 2.2.5 Path Loss

Path loss, as a radio propagation concept, refers to the phenomenon of power density decrease of an electromagnetic wave, as it propagates through space. Path loss is a determining factor in analyzing the link budget (accounting of all gains and losses from the transmitter to the receiver through a particular medium) of a telecom system [10].

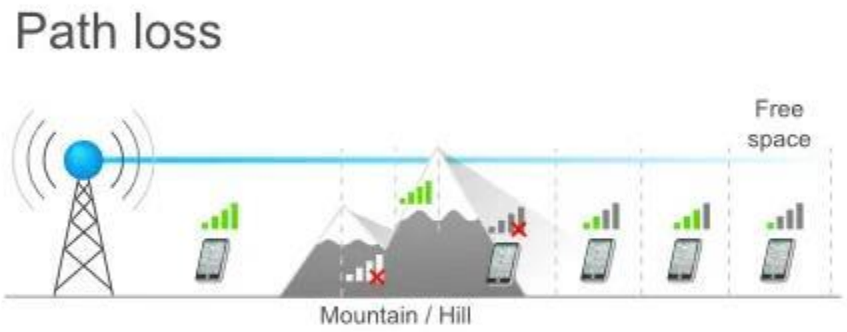

Figure 2.3:Figure showing path loss *[10]*.

Path loss can be caused by various factors: refraction, diffraction, free-space loss, reflection, aperture-medium coupling loss, or absorption. Other variables in determining the path loss are the environment, the type of terrain, the medium of propagation, the distance between the emitter and the receiver, or the type and mounting of the antennas [10].

Path losses occur during the natural expansion of radio waves in the free space, when the signal is obstructed by an impenetrable obstacle, or when the signal's medium of transmission is not transparent to electromagnetic waves [10].

Multipath is an effect related to path loss and is caused by a signal transported from the transmitter to the receiver through multiple different paths. Thus, the signal arriving at the receiver is variable, depending on the distribution of intensity, and the propagation time, and the bandwidth of the transmitted signal [10].

Small scale fading is another phenomenon caused by rapid changes in the radio signal amplitude in a short time frame or on a short distance.

Free space path loss can be given by

$$L = \frac{P_t}{P_r} = \left(\frac{4\pi l}{\lambda}\right)^2 = \left(\frac{4\pi l f}{c}\right)^2 \qquad (2)$$

Where $\lambda$ the wavelength, c is the speed of light, l is the transmission distance, and f is the frequency of the radio signal [10].

Prediction Models

Free space path loss, also expressed as $1/r^2$ is an elementary model to be considered when designing a radio communications system. It is the standard free-space loss caused by the expanding wavefront area, as the wave travels through free space.

Other widely used path loss prediction models are Hata, Cost231, or Walfisch-Ikegami. They are based on measured and averaged losses through various classes of radio links [10].

## 2.3 Shadow Fading

An evident lack of verified and comprehensive theoretical models for shadow fading, which enable analytical estimation of its statistical distribution and statistical parameters, has promoted the empirical alternatives for this task in many aspects of a wireless system lifecycle, such as e.g. coverage planning, where the imperative is to determine the optimal number of base stations, which balances the system performance and implementation efficiency. However, in addition to shadow fading, the composite received signal is simultaneously affected by deterministic path loss and multipath fading, too, so the prerequisite for accurate estimation of shadow fading from the composite received signal samples is efficient elimination of its fast temporal variations, fast spatial variations, and finally, path loss. Unfortunately, the available methods for this are often not appropriate for measurements related to shadow fading estimation. So, for example, even the commonly used drive/walk test provides neither elimination of time variations, nor accurate path loss estimation. So, in this paper, after identifying drawbacks of the existing techniques for shadow fading estimation, the appropriate procedure is proposed with concrete and unambiguous guidelines for the elimination of undesirable components of the composite signal through a five-step algorithm, which is shown to provide a significant advantage for common drive/walk testing, in terms of shadow fading values and its statistical parameters estimation [11].

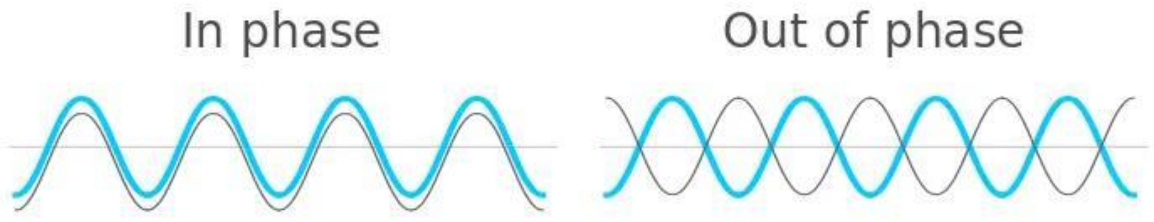

Figure 2.4Figure showing shadow fading *[10]*.

### 2.3.1 Multipath Fading

Multipath fading is a feature that needs to be taken into account when designing or developing a radio communications system. In any terrestrial radio communications system, the signal will reach the receiver not only via the direct path but also as a result of reflections from objects such as buildings, hills, ground, water, etc that are adjacent to the main path [10].

At times there will be changes in the relative path lengths. This could result from either the radio transmitter or receiver moving, or any of the objects that provide a reflective surface moving. This will result in the phases of the signals arriving at the receiver changing, and in turn, this will result in the signal strength varying as a result of the different way in which the signals will sum together. It is this that causes the fading that is present on many signals [10].

### 2.3.2 Rayleigh Fading

When no LOS path exists between transmitter and receiver, but only have an indirect path then the resultant signal received at the receiver will be the sum of all the reflected and scattered waves [12].

### 2.3.3 Rician Fading

It occurs when there is a LOS as well as the non-LOS path in between the transmitter and receiver, i.e. the received signal comprises both the direct and scattered multipath waves [12].

### 2.3.4 Selective and Flat Fading

Multipath fading can affect radio communications channels in two main ways. This can be given how the effects of the multipath fading are mitigated [10].

Flat Fading*:* This form of multipath fading affects all the frequencies across a given channel either equally or almost equally. When flat multipath fading is experienced, the signal will just change in amplitude, rising and falling over some time, or with movement from one position to another [10].

Selective Fading*:* Selective fading occurs when the multipath fading affects different frequencies across the channel to different degrees. It will mean that the phases and amplitudes of the signal will vary across the channel. Sometimes relatively deep nulls may be experienced, and this can give rise to some reception problems. Simply maintaining the overall amplitude of the received signal will not overcome the effects of selective fading, and some form of equalization may be needed. Some digital signal formats, e.g. OFDM can spread the data over a wide channel so that only a portion of the data is lost by any nulls. This can be reconstituted using forward error correction techniques and, in this way, it can mitigate the effects of selective multipath fading [10].

Selective multipath fading occurs because even though the path length will be changed by the same physical length (e.g. the same number of meters, yards, miles, etc) this represents a different proportion of a wavelength. Accordingly, the phase will change across the bandwidth used [10].

Selective fading can occur over many frequencies. It can often be noticed when mediumwave broadcast stations are received in the evening via ground wave and skywave. The phases of the signals received via the two means of propagation change with time and this causes the overall received signal to change. As the multipath fading is very dependent on path length, it is found that it affects the frequencies over even the bandwidth of an AM broadcast signal to be affected differently and distortion results [10]. Selective multipath fading is also experienced at higher frequencies, and with high data rate signals becoming commonplace wider bandwidths are needed. As a result, nulls and peaks may occur across the bandwidth of a single signal [10].

### 2.3.5 Fast Fading

It varies quickly with the frequency. Fast fading originates due to the effects of constructive and destructive interference patterns that are caused due to multipath. Doppler spread leads to frequency dispersion and time selective fading [13]. Fast fading results due to high Doppler Spread, Coherence Time < Symbol Period, Channel impulse response changes rapidly with the symbol duration, occurs if Ts> Tc, Bs< Bd, it occurs for very low data rates [13].

### 2.3.6 Slow Fading

It does not vary quickly with the frequency. It originates due to the effect of mobility. It is a result of signal path change due to shadowing and obstructions such as trees or buildings etc [13]. Slow fading results due to low Doppler Spread, Coherence Time >> Symbol Period, impulse response changes much slower than the transmitted signal, it occurs if Ts<<Tc, Bs>>Bd [13].

## 2.4 Radio Interference

Radio Interference is the phenomenon that disrupts a signal as it travels on a channel from the transmitter to the receiver. The disturbance may interrupt, obstruct, degrade, or limit the effective reception of signals. These effects can range from a simple degradation of data to a total loss of data.

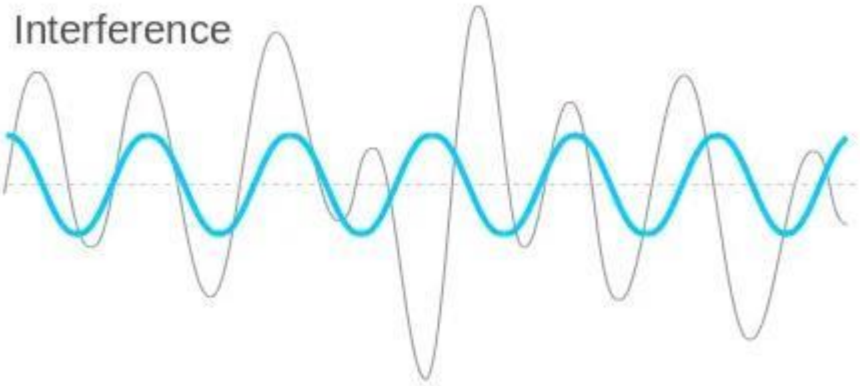

Figure 2.5: Figure showing the interference of signals *[10]*.

There are several types of radio interference such as Co-channel interference which is caused by two transmitters using the same frequency, Unintentional interference (EMI) caused by a source that radiates power in the same range as other equipment, Adjacent-channel interference (ACI) caused by the external power of a signal from an adjacent channel: inadequate filtering, poor frequency control, etc.

### 2.4.1 Multipath Propagation

Multipath is a propagation phenomenon that causes the transmitted signal to be sent on two or more paths to the receiver. The most frequent causes of multipath propagation are refraction, reflection from water sources or objects such as mountains and buildings, atmospheric ducting, and ionospheric reflection [14].

Therefore, multipath propagation causes the reflected radio waves to interfere with the direct line of sight radio waves, resembling a typical echo effect. This is a common phenomenon and mobile networks are designed to minimize the damaging effects of reflections [14].

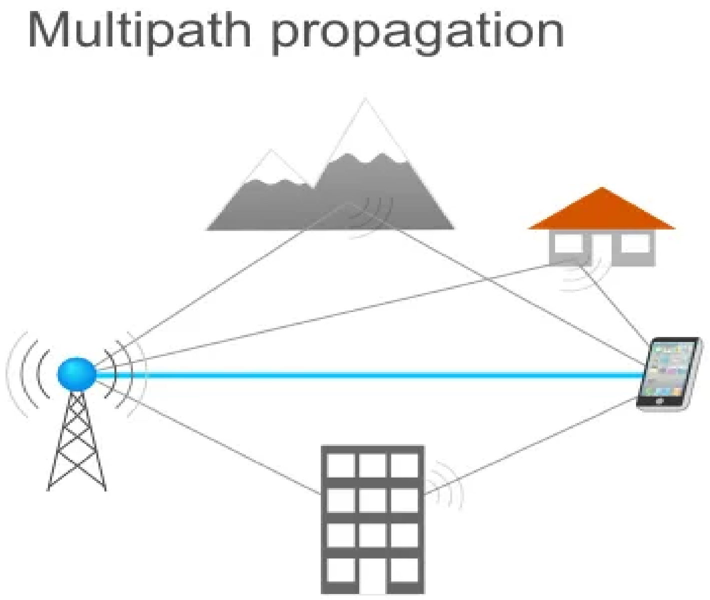

Figure 2.6: Figure showing multipath propagation *[10]*.

## 2.5 Circle Packing of Overlapped Circles

In circle packing, a given number of circles with equal radius should be arranged inside or outside a given surface for no overlap or overlapped circles. The radius of each circle decreases as the number of circles increases. For each number of UAVs, a specific packing strategy needs to be used for example. Upper bounds on packing density in a circle let D be the maximum density of packing n circles in a unit circle. Considering many circles of equal diameter d that are needed to be packed in a circle of radius $1 + \frac{\square}{2}$. You find that the centers of the circles are in the closest unit circle [15].

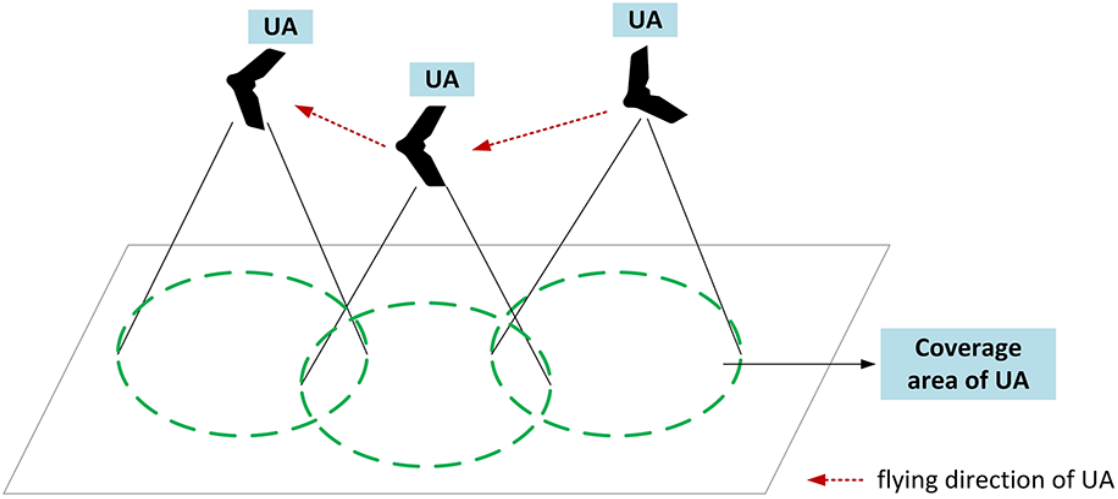

Figure 2.7: Figure showing overlapped circle packing *[16]*.

## 2.6 Probability of Line-of-Sight in Urban Environments

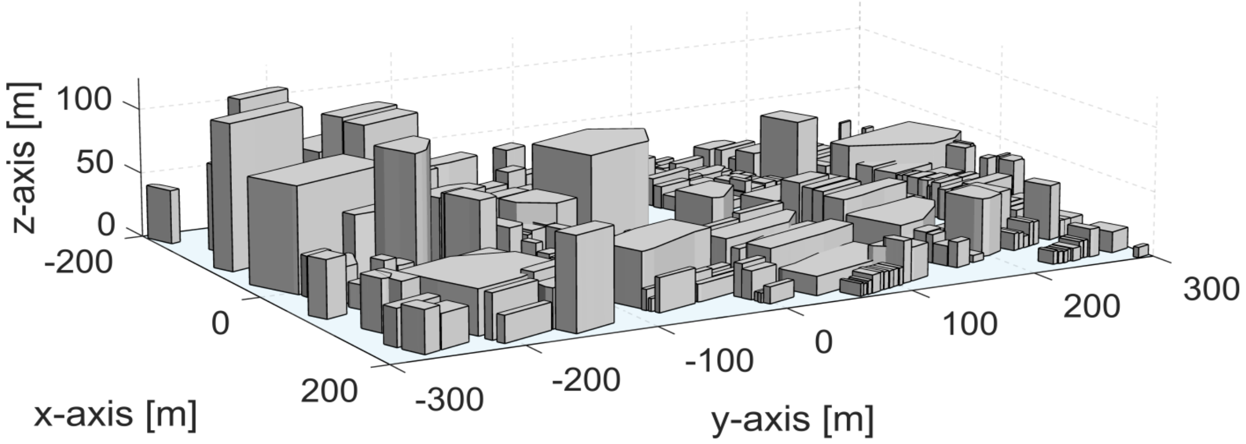

Figure 2.8: Figure of Probability of LoS in Urban Environment *[17]*.

Line-of-Sight communication will play a major role in the next generation of wireless technologies; from UAV-to-UAV networks, to land mobile satellite services, and mm-Wave cellular coverage. Predicting the geometric line-of-sight probability in different urban environments formulated based on stochastic geometry. The model combines the simplicity of formulation with a high degree of accuracy when compared to real-life geographic data. For two points in the 3D space, it takes the height of each point and the distance between them as input, also it takes 4 other simple parameters that describe the geometric properties of the underlying environment. Based on these inputs, the proposed model produces consistent analytic results aligned with the ray-tracing of the geographic data. Availability of line-of-sight (LoS) has a large effect on the performance of wireless channels; this influence becomes even more important for applications like mmWave, land mobile satellite, and UAV communications that are envisioned to take a prominent role in the next wave of hybrid communication systems. In these applications, the wireless signal is either too weak to be delivered using non-line of sight modes (the case of UAV and satellites) or it does suffer from an extreme penetration loss due to absorbent obstacles (the case of mmWave). Throughout the years, there have been many good models to capture the LoS probability developed by researchers and engineers, where the majority are specific to certain applications (or scenarios). The most known of which are the models recommended by the International Telecommunication Union focusing on common cellular scenarios such as Macro and Microcellular sites with the restriction on the acceptable range of node heights. With the advent of mmWave in 5G, extensive empirical studies have been conducted by researchers and industry to determine the radio LoS probability as part of the overall efforts in studying the propagation properties of mmWave. 3GPP is also actively working on expanding its traditional 2D-based channel models into 3D incorporating the LoS probability, this mainly stems from the intrinsic limitation of planner models in capturing mmWave and high-rise indoor scenarios. Most of the mentioned studies are based on empirical measurements without the need to rely on developing complicated geometrical models [17].

## 2.7 3-D placement of UAVs for Congestion Mitigation in Cellular Networks

Although many 3-D drone-cell placement problems have been developed, there a few of them that consider the problem of deploying drone-cells to cover devices of different QoS requirements. Most of them exploit the problem of offloading the maximum number of devices of similar QoS requirements to drone-cells under certain constraints. Owing to various QoS requirements, devices of high QoS requirements may not be served although they are in the coverage region of a drone-cell. Further, it may be crucial to investigate the 3-D drone-cell placement problem for devices of different QoS requirements in future cellular networks. For example, large screen devices (e.g., tablets) may require a high data rate to display content at a high resolution; thus, large-screen devices may be more sensitive to QoS than small-screen devices (e.g., mobile phones and small smartphones) [18].

The QoS requirement is the measure of a user-required data rate. We perform fundamental analysis on this problem and propose four algorithms to obtain a suboptimal location of the drone-cell. Very recently, Chen *et al.* formulated a drone-cell placement problem to maximize users' quality-of-experience (QoE) while minimizing drone-cells' transmission power. In this work, different users might have different QoE that was measured by both transmission delay and data rate requirement. Deploying one drone-cell to mitigate congestion in cellular networks. Considers deploying multiple drone-cells to cover a geographical area unlike our work, the goal of is to deploy drone-cells effectively to enhance the QoE of each device while minimizing the transmit power of drone-cells; 3) we have no restriction on the capacity of a drone-cell. Assumes that the total bandwidth available for each drone-cell is limited. Furthermore, formulates a 2-D drone-cell placement problem and does not perform theoretical analysis on the formulated problem. Besides, adopts the learning algorithm proposed to find suboptimal horizontal locations for drone-cells [18].

# Chapter 3

## 3 Methodology

Chapter 3 discusses the practical concepts introduced in the previous chapter for literature review detailing the aspects of the project which include; tools, the system model, channel models, problem formulation, and simulation parameters.

### 3.1 Tools

The simulation is done using MATLAB software which can simulate the optimal placement of UAVs using a set of parameters in a given geographical area and precise simulation results and performance analysis.

### 3.2 System Model

This section discusses the system model and some of the assumptions that have been taken to carry out this research.

#### 3.2.1 Network Topology

We consider a wireless communication system with UAV base stations

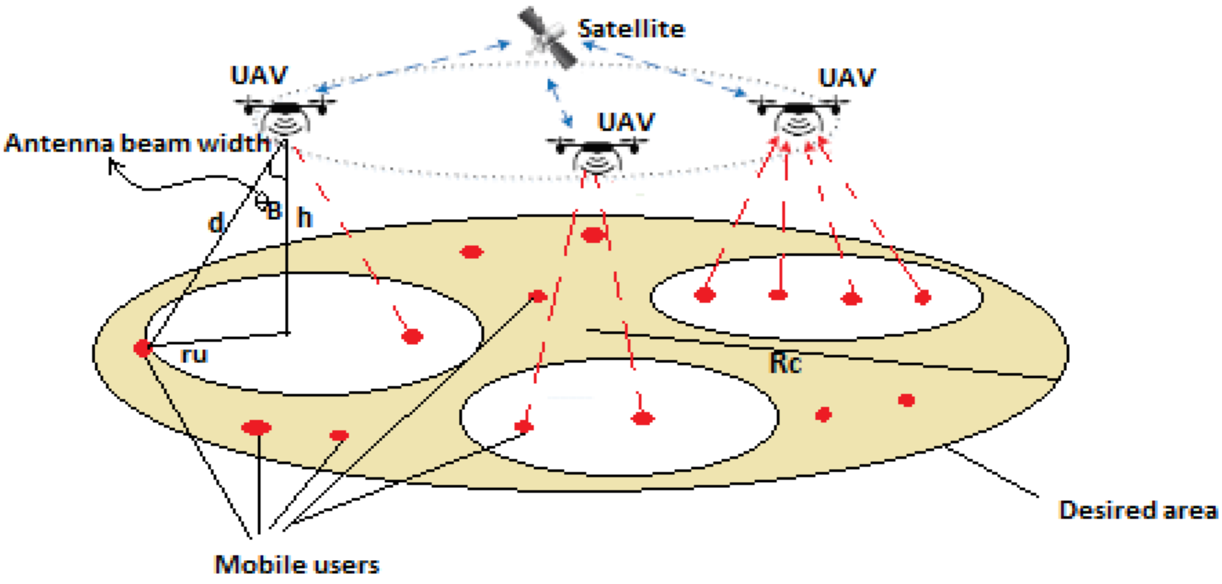

Figure 3.1: Figure showing the network topology

We consider a circular geographical area of radius $\square_{\square}$, in an urban environment as shown above, within which *M UAVs* must be deployed to provide wireless coverage for ground users located within that area. In this model, we consider a stationary LAP such as quadrotor UAVs.

The UAVs are assumed to be symmetric having the same transmit power and altitude.

We consider ten UAVs to be deployed in a given geographical area

We assume also assumes that the target area is circular with a radius $\square_{\square}$=5000m and we also consider that UAVs are backhauled by satellite.

For the air-to-ground channel modeling, we considered the LoS and non-line-of-sight (NLoS) links between the UAV and the ground users separately. Each link has a specific probability of occurrence which depends on the elevation angle, environment, and relative location of the UAV and the users. Clearly, for NLoS links the shadowing and blockage loss is higher than the LoS links. Therefore, the received signal power from UAV *j* at a user's location can be given by

$$\square_{\square},\text{j(dB)}= \{ \begin{array}{l} \square_{\square} + \square_{\square\square} - \square_{\square\square} - \psi_{\square\square\square,} \;\; \square\square\square\ \square\square\square\square \\ \square_{\square} + \square_{\square\square} - \square_{\square\square} - \psi_{\square\square\square\square,} \;\; \square\square\square\square\ \square\square\square\square \end{array} \qquad (3)$$

Where $\square_{\square,\square}$ is the received signal power, $\square_{\square}$ is the UAV's transmit power, and $\square_{3\square\square}$ is the UAV antenna gain in dB, and $\square_{\square\square}$ is the path loss for the air to ground communication.

We considered the Probabilistic LoS/NLoS links to determine the downlink coverage probability.

The LoS Probability is $\square_{\square\square\square,J}$ =α($\frac{180\ \theta_{\square}}{\pi}$ − 15) $^{\gamma}$ (4)

Where $\square$ and γ are constant values that depend on the environmental impact, and

$$\theta_{\square} = \sin^{-1}(h/\square_{\square}). \qquad (5)$$

Therefore $\square_{\square\square\square\square,J}$ is given by;

$$\square_{\square\square\square\square,J} = 1- \square_{\square\square\square,J} \qquad (6)$$

Mean and variance of LOS and NLOS links

$$\square_{\square\square\square}(\theta_{\square}) = \square_{1}\square\square\square(-\square_{2}\theta_{\square}) \qquad (7)$$

$$\square_{\square\square\square\square}(\theta_{\square}) = \square_1\square\square\square(-\square_2\theta_{\square}) \qquad (8)$$

Where$\theta_{\square} = \sin^{-1}(h/\square_{\square})$, the elevation angle between the UAV and the user, $\square_1, \square_2, \square_1$, $\square\square\square$ $\square_2$are constant values that depend on the environment.

## 3.3 Channel Models

For the air to ground communication between the UAV and any ground user the, path loss L can be expressed as below where d is the distance between UAV j and ground user, c is the speed of light and $\square_{\square}$ is the carrier frequency and n≥2 is the path loss exponent.

$$\square_{\square\square} = 10n\log\left(\frac{4\pi \frac{\square}{\square}\square\square}{\square}\right) \qquad (9)$$

Where $\square_{\square}$ the distance between UAV j and a ground user, n≥2 is the path loss exponent is the speed of light, and $\square_{\square}$ is the carrier frequency.

This section considers path loss models for both indoors and outdoors and both LOS and NLOS. UAVs use the air to the ground channel to communicate with the ground terminals. The air to ground model has two parts, LOS and NLOS path loss. Basing on the location between the UAV and the receiver, a probability is calculated. The basic parameters considered are the distance between the transmitter and the receiver, the altitude of transmitting, and the beamwidth. The formulas are detailed as below:

$$\square_{\square\square\square} = 20\log\left(\frac{4\pi\ \square_{\square}\ \square_{3D}}{\square}\right) + \square\square_{\square\square\square} \qquad (10)$$

$$\square_{\square\square\square\square} = 20\log\left(\frac{4\pi\ \square_{\square}\ \square_{3D}}{\square}\right) + \square\square_{\square\square\square\square} \qquad (11)$$

$$\square_{\square\square\square} = \frac{1}{1+\square\square x\square(-[\frac{180}{\pi}\theta-\square])} \qquad (12)$$

$$\square_{\square} = \square_{\square\square\square} \times \square_{\square\square\square} + \square_{\square\square\square\square} \times \square_{\square\square\square\square}$$

(13)

Where $\square_{\square}$ is the total path loss containing two parts for $\square_{\square\square\square}$ and $\square_{\square\square\square\square}$.

### 3.3.1 Shadowing and Blockage Loss

Shadowing and blockage losses are more dominant in NLoS links.

The shadow fading with normal distribution due to line of sight link is $\psi_{\square\square\square}$ ~N($\square_{\square\square\square}, \sigma^2{}_{\square\square\square}$)

and the shadow fading with normal distribution due to non-line of sight link is $\psi_{\boxed{?}\boxed{?}\boxed{?}\boxed{?}}$

~N(□$_{□□□□□}$ ,$\sigma^2{}_{□□□□□}$ ) where $\sigma^2{}_{□□□}$ is the variance due to LoS link,□$_{□□□}$ is the mean due to LoS link and □$_{□□□□}$ is the mean due to NLoS link and $\sigma^2{}_{□□□□}$ is the variance due to the NLoS link.

### 3.3.2 Optimal Multi-UAV Deployment.

We found the coverage radius □$_□$ of each UAV in presence of interference from other UAVs and here we derived the coverage probability of a single UAV from which we came up with a deployment strategy for the UAVs that maximizes the total coverage performance while maximizing coverage lifetime. The coverage radius of a UAV,□$_□$, is the maximum range within which the probability that users are covered by the UAV is greater than a certain threshold,ε, number of UAVs, and UAVs' location. Therefore

$$□_□ = □□□\{□|□_{□□□}(□, □_□, \theta_□)|\}$$

(14)

We found the coverage radius of each UAV given by;

□□□□□ □$h$□□ □$_□$ $= 5000□$ and is the radius of the geographical area to be covered.

The radius of each circle decreases as the number of circles or UAVs increase

## 3.4 Problem Formulation

From theorem 1, we consider a ground user located at a distance □ $\le h.\tan\left({}^{\theta_□}/_2\right)$ from the projection of the UAV j on the desired area to determine the coverage probability;

$$□_{□□□} = □_{□□□,□}\,□\left(\frac{□\ □□\ □ + □□B - □_□ - G\ 3□B + □\ \ L\ □□}{\delta_{L□□}}\right) + □_{□□□,□}\,□\left(\frac{□\ □□\ □ + □□B - □_□ - G\ 3□B + \ \ □\ L\ □□}{\delta_{L□□}}\right) \quad (15)$$

Where □$_{□□□}$ = 10log(□□ + □$I$) is the minimum received power requirement in dB for successful detection, N is the noise power, **β** is the signal-to-interference-plus-noise-ratio (SINR) threshold and$I$ is the mean interference power received from the nearest UAV k given by;

$$□ = □_{□□(\varphi□)}\left[10^{\frac{-\mu L\ □□}{10}}□_{□□□,□} + 10^{\frac{-\mu□L\ □□}{10}}□_{□□□□,□}\right]\left(\frac{4\pi\ □_□\ □_□}{□}\right)^{-□} \quad (16)$$

Where ⍰⍰⍰⍰ and ⍰⍰⍰⍰⍰ are mean for LOS and NLOS respectively.

Theorem 1 shows that changing the UAV’s location affects the distance between the users and the UAV, LOS probability. When the UAV altitude increases, it also increases the path loss, increasing the LOS probability, which also increases a higher feasible radius. The UAVs’ transmit power need to be increased in the presence of interference which helps to meet the coverage requirements.

Increasing the number of UAVs decreases the distance between UAVs which leads to an increase in interference to the nearest UAV.

$□_{□□}$ is the path loss for the air to ground channel modeling given by;

$$□_{□□} = 10n\log\left(\frac{4\pi\, □_{□}\, □_{□}}{□}\right)$$

Where $□_{□}$ the distance between UAV j and a ground user, n≥2 is the path loss exponent is the speed of light, and $□_{□}$ is the carrier frequency.

$$□_{□□} \approx \frac{2900\ 0}{{\theta_B}^2}, \qquad (17)$$

Is the main lobe gain where $\theta_{□}$ the antenna half beam width in degrees.

The LoS probability is given by;

$$□_{□□□,J} = \alpha\left(\frac{180}{\pi}\theta_{□} - 15\right)^{\gamma}$$

Where α and γ are constant values reflecting the environmental impact and the NLoS is given by;

$$□_{□□□□,J} = 1 - □_{□□□,J}$$

The shadow fading with normal distribution due to line of sight link is $\psi_{□□□} \sim N(□_{□□□}, \sigma^2_{□□□})$ and the shadow fading with normal distribution due to the non-line of sight link is $\psi_{□□□□} \sim N(□_{□□□□}, \sigma^2_{□□□□})$ where $\sigma^2_{□□□}$ is the variance due to LoS link, $□_{□□□}$ is the mean due to LoS link

and $\square_{\square\square\square\square}$ is the mean due to NLoS link and $\sigma^{2}{}_{\square\square\square\square}$ is the variance due to the NLoS link

Mean and variance of LOS and NLOS links

$$\square_{\square\square\square}(\theta_{\square}) =$$

$$\square_{1}\square\square\square(-\square_{2}\theta_{\square})$$

$$□_{□□□□}(\theta_{□}) = □_1□□□(-□_2\theta_{□}$$

$$),$$

Where$\theta_{□} = \sin^{-1}(h/□_{□})$, the elevation angle between the UAV and the user, $□_1, □_2, □_1, □□□$
$□_2$
are constant values that depend on the environment.

Where $□_{□}$ is the total path loss containing two parts for $□_{□□□}$ and $□_{□□□□}$.

### 3.4.1 Coverage Lifetime

From the coverage radius of the UAV,$□_{□}$, which is the maximum range within which the probability that users are covered by a UAV is greater than the specified threshold. The coverage radius depends on antenna beamwidth, ε, transmit power, UAVs' location, and the number of UAVs.

Therefore, the coverage radius is given by:

$$□_{□} = □□□\{□|□_{□□□}(□, □_{□}, \theta_{□}$$

$$)|\}$$

Coverage lifetime is the time taken by a UAV to give coverage to ground users. To maximize the coverage lifetime, each UAV must use a minimum transmit power.

Assuming a circular geographical area, the problem formulated is:

$$(\vec{□}^{*}_{□}, h^{*}, □^{*}_{□}) = \arg\underset{□_{□}}{□□□□}.\,^{2} \qquad (18)$$

$$□ \in \{1, \ldots., □\} \qquad (19)$$

$$□□.\,\|\vec{□}_{□} - \vec{□}_{□}\| \geq 2□_{□}, \quad □ \neq □ \in \{1, \ldots., □\}$$

$$(20)$$

$$\|\vec{□}_{□} + \vec{□}_{□}\| \leq □_{□}$$

$$(21)$$

$$⍰_{⍰} \leq h.\tan\left({}^{\theta_{⍰}}/_{2}\right) \qquad (22)$$

Where $⍰_{⍰}$ the radius of the desired area, M is the number of UAVs, $⍰_{⍰}$ is the maximum coverage radius, $\vec{⍰}_{⍰}$ is vector location of UAV j in the 2-dimension plane of the desired area.

### 3.4.2 Circle Packing Problem

Circle packing is used for UAV optimal placement with overlapping circles.

Considering five circles or UAVs to give coverage to mobile users in a unit circle, the radius is given by;

$$r\,(5) = \Phi - 1 = 0.609 \qquad (23)$$

Where $\Phi = \frac{1+\sqrt{5}}{2}$, therefore, 0.609 is the radius for 5 UAVs to give coverage

Therefore, the coverage radius for five UAVs on to the desired area is $0.609\square_{\square}$

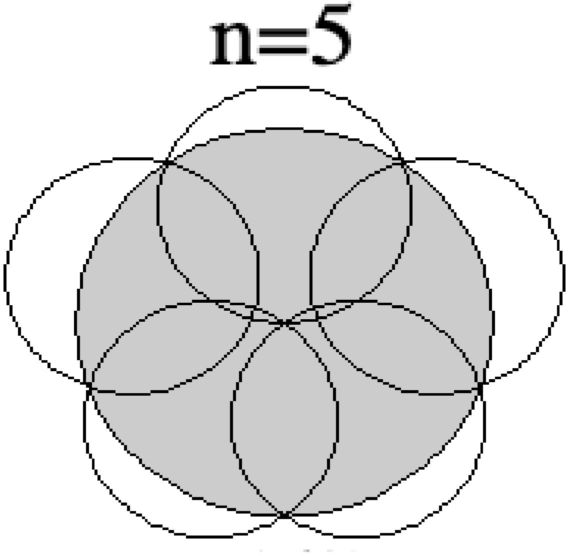

Figure 3.2: Figure showing 5 circles being packed in a unit circle

In the circle packing problem, M (number of UAVs) circles should be arranged inside a given geographical area such that the packing density is maximized and the circles overlap. In our model, each circle corresponds to the coverage region of each UAV, and maximizing packing density is related to maximizing the coverage area with overlapping smaller circles. The radius of each circle decreases as the number of circles increases

We consider increasing the coverage radius of the UAVs by increasing their height accordingly so that the circles can overlap.

**Maximum packing density**

We found the maximum packing density (D) of a circle using M equal smaller circles using;

From $$\square \leq \frac{\square\ \square_{\square}^{2}}{(2+\square_{\square})^2} \qquad (24)$$

$$D = \square\ \frac{\square_{\square}^{2}}{\square_{\square}^{2}} \qquad (25)$$

2 2

Equating the two equations gives

$$\frac{\square\ \square_{\square}}{\square_{\square}^{2}} \leq \frac{\square}{(2+\square_{\square})^{2}} \tag{26}$$

$\square_{\square}$

Thus $$\square_{\square} \leq \frac{\square_{\square}\,\square_{\square}}{(2+\square_{\square})} \qquad (27)$$

Each circle corresponds to the coverage density of each UAV; the maximum total coverage density is related to the coverage area of the overlapped circles of the UAVs' coverage.

The antenna beamwidth is given by using the UAV height from the user

$$h = \frac{\square_{\square}}{\tan({}^{\theta_B}/_{2})} \qquad (28)$$

Making $\square_{\square}$ □$h$□ □□□□□□□ $$\square_{\square} = \mathrm{h.}\tan\left({}^{\theta_{\square}}/_{2}\right) \qquad (29)$$

Therefore $$h \leq \frac{\square_{\square}\ \square_{\square}}{\tan({}^{\theta_B}/_{2})(2+\square_{\square})} \qquad (30)$$

The next step is to calculate the packing density of the UAV to give the maximum total coverage density. Considering five UAVs as our example.

Using M = 5, $\square_{\square} = 5000$, $\square_{\square} = 5\square_{\square}$

From equation 25, D is calculated as;

$$\square = \frac{5 * (5 * 500_{2}0)}{(5000)^{2}}$$

$$\square = 1.854$$

The maximum total coverage density given by five UAVs is 1.854

Where M is the number of UAVs, $\square_{\square}$ is the coverage radius of each circle or UAV and $\square_{\square}$ is the radius of the desired geographical area

Covering a circular area with a radius $\boldsymbol{R_c}$ using identical UAVs-the circle packing in a circling approach

Table 3.1: Table of coverage radius and maximum packing density

| Number of UAVs | Smallest radius r(n) | Coverage radius of each UAV | Maximum total coverage density (D) |
|---|---|---|---|
| 1 | 1 | $\square_{\square}$ | 1 |
| 2 | 1 | $\square_{\square}$ | 1 |
| 3 | 0.866 | $0.866\square_{\square}$ | 2.25 |
| 4 | 0.707 | $0.707\square_{\square}$ | 1.999 |
| 5 | 0.609 | $0.609\square_{\square}$ | 1.854 |
| 6 | 0.555 | $0.555\square_{\square}$ | 1.848 |
| 7 | 0.5 | $0.5\square_{\square}$ | 1.750 |
| 8 | 0.437 | $0.437\square_{\square}$ | 1.528 |
| 9 | 0.422 | $0.422\square_{\square}$ | 1.60 |
| 10 | 0.398 | $0.398\square_{\square}$ | 1.584 |

### 3.4.3 Optimal UAVs Base Station Placement Algorithm

To provide wireless communication, the UAV base stations can be deployed and adjusted based on the users' requirements and distributions. We assume that each ground user needs to be covered continuously by a UAV to ensure uninterrupted communication. The efficient 3D placement algorithm for overlapped UAV placement is proposed. The height of each UAV h is determined.

We adopted the vacancy search technique (BFGS) because of its deterministic arrangement of packing.

### Search space formation

In our consideration, equal circles are packed to cover a circular desired area, let the radius of the desired circle (unit circle) r = 1, the objective is to uniformly arrange the unit circles to cover the circular area with overlapping so that the desired area s is expected to be covered.

Given $(□^*_□, h^*, □_□) = \arg □□□□.$ $^2$ unit circles with their coordinates, $□(□\epsilon□^+)$.

$$□_□ \qquad □' = [□, □] = \begin{bmatrix} □_1 & □_1 \\ □_2 & □_2 \\ □_3 & □_3 \\ \cdots & \\ □_□ & □_□ \end{bmatrix} \qquad (31)$$

$$□_{□□} = \sqrt{(□_□ - {}^2 + (□_□ - □_□)^2} \geq 2 \times □, □, □, □ = □^+ □ \neq □ \; □_□) \qquad (32)$$

Let (Xbl' Ybl) be the bottom-left coordinate of the square container, dij be the center distance between circle i and j [19].

### The overlapped UAV placement algorithm

```
Procedure Overlapped circle packing ($□_□$).      A circle packing $□_□$ of M circles
  $□ \leftarrow □ * 2$                          Initialization of desired area s
    $□ \leftarrow □_0$
    $□ \leftarrow □(□)$
    $□ \leftarrow 1$
    $h \leftarrow □□□$
    while $h \looparrowright □$ do
      $□(□) \leftarrow □□□□\ □□□□□□□□□□\ □□□□(□)$
```

```
⍰ ← ⍰⍰⍰⍰(⍰, ⍰)
Minimise f Eq (18) value
```

```
                **if** E(p) > eps **then**
                    $□ \leftarrow □□□□(□, □)$
            **end if**
                $h \leftarrow □(□)$
                **if** $h \underset{□^{□} \leftarrow □}{<} □$ **then**
                    $□ \leftarrow h$
**end if**
            $□ \leftarrow □ + 1$
            **if** $□ > □$ **then**
            $□ \leftarrow 1$
            **end if**
        **end while**
        **Return** $□'$
    **end procedure**
```

## 3.5 Simulation Parameters

Table 3.2: Simulation parameters and values

| | |
|---|---|
| Carrier frequency ($⍰_{⍰}$) | 2GHz |
| In an Urban environment constant ⍰ | 0.6 |
| Urban environment constant γ | 0.11 |
| Environmental constant $⍰_1$ | 10.39 |
| Environmental constant $⍰_2$ | 0.05 |
| Environmental constant $⍰_1$ | 29.06 |
| Environmental constant $⍰_2$ | 0.03 |
| Mean of shadow fading for LoS (⍰⍰⍰⍰) | 1dB |
| Mean of shadow fading for NLoS (μNLoS) | 20dB |
| Path loss exponent (n) | 2.5 |
| The threshold for coverage radius (ε) | 0.08 |
| Signal-to-interference-plus-noise-ratio (SINR) threshold (⍰) | 5 |
| Noise power (N) | -120dBm |
| UAV altitude (h) | h<5000m |
| The radius of the desired area ($⍰_{⍰}$) | 5000m |
| Half beam width ($\theta_{⍰}$) | $80^0$ |
| Power transmitted ($⍰_{⍰}$) | 35dBm |

# Chapter 4

## 4 Simulation Results and Analysis

This chapter discusses the simulation results and analysis of the proposed algorithm

### 4.1 Total Coverage against the Number of UAVs

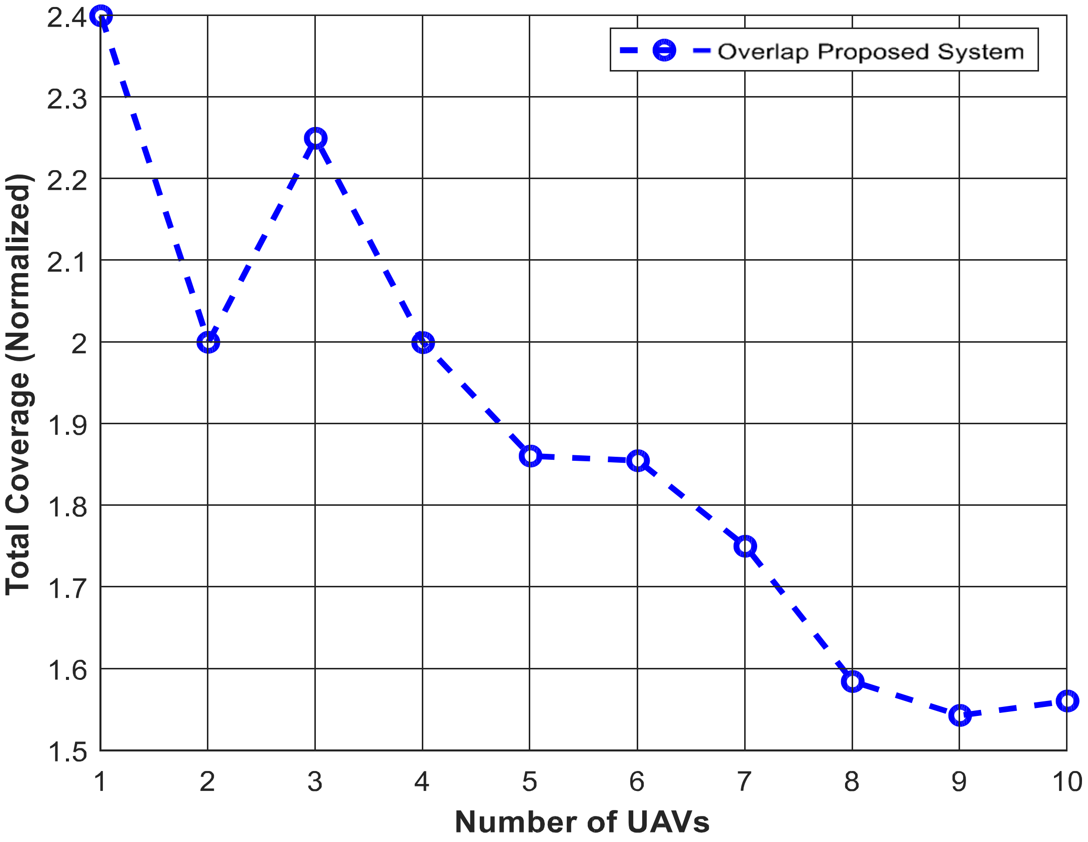

Figure 4.1: Figure showing the variation of total coverage against the number of UAVs

Simulation conclusion on total coverage against the number of UAVs.Figure: 3, shows that a single UAV has the highest total coverage because its altitude can be easily increased to give maximum coverage to the entire desired area, and the highest coverage threshold is achieved when three UAVs are deployed.

## 4.2 Coverage Lifetime

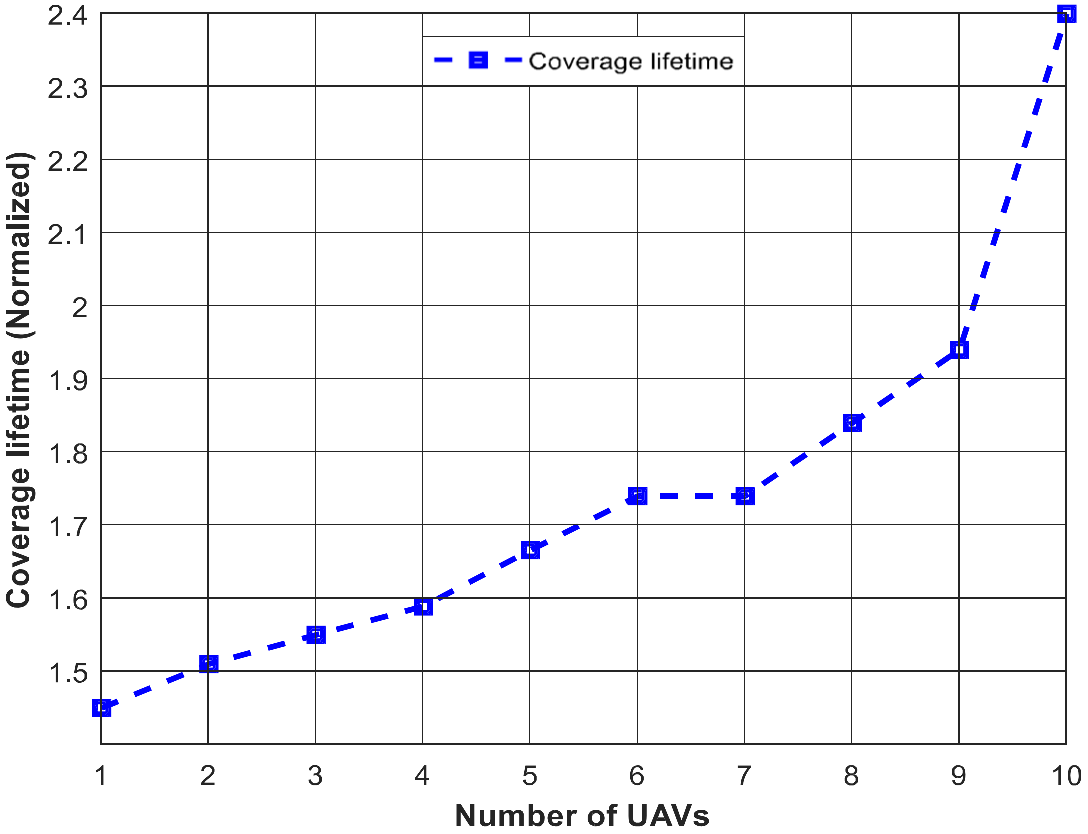

Figure 4.2: Figure showing coverage lifetime against the number of UAVs

Simulation conclusion on coverage lifetime against the number of UAVs.Figure: 4, shows that with increasing the number of UAVs, the coverage lifetime increases due to the decrease in the transmit power of each UAV. As the number of UAVs increases, the coverage area of a single UAV is reduced hence increasing coverage lifetime. This is achieved by lowering the UAVs' altitudes and decreasing transmits power. However, having a single UAV yields a minimum coverage lifetime

## 4.3 UAV altitude versus the Number of UAVs

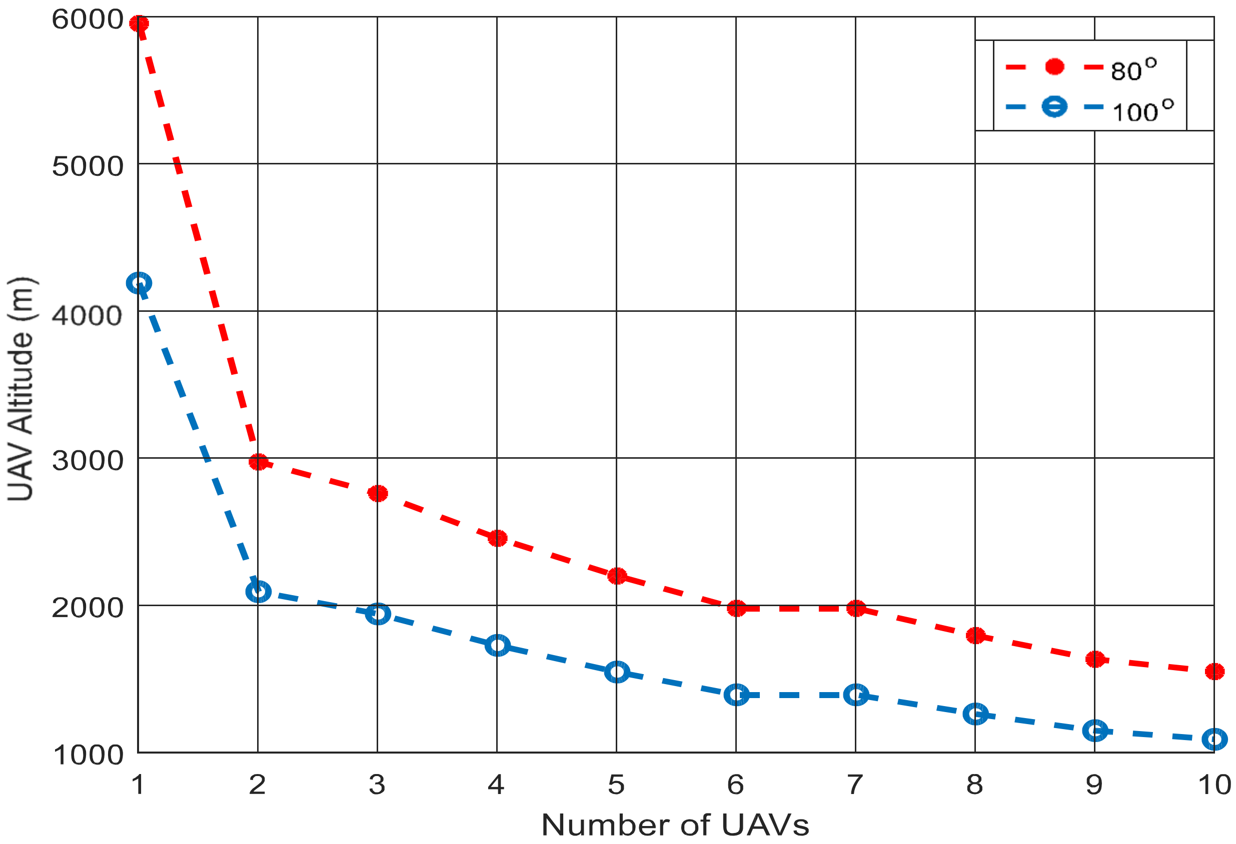

Figure 4.3: Figure showing the variation of UAV altitude with the number of UAVs

Conclusion on UAVs altitude against the number of UAVs.Clearly, figure 5 shows that the altitude of UAVs decreases as the number of UAVs increase. Doubling the number of UAVs from 3 to 6 decreases altitude from 2000m to about 1300m.

A single UAV has the highest altitude to provide coverage to the whole coverage area

## 4.4 Number of required UAVs versus radius of the desired area

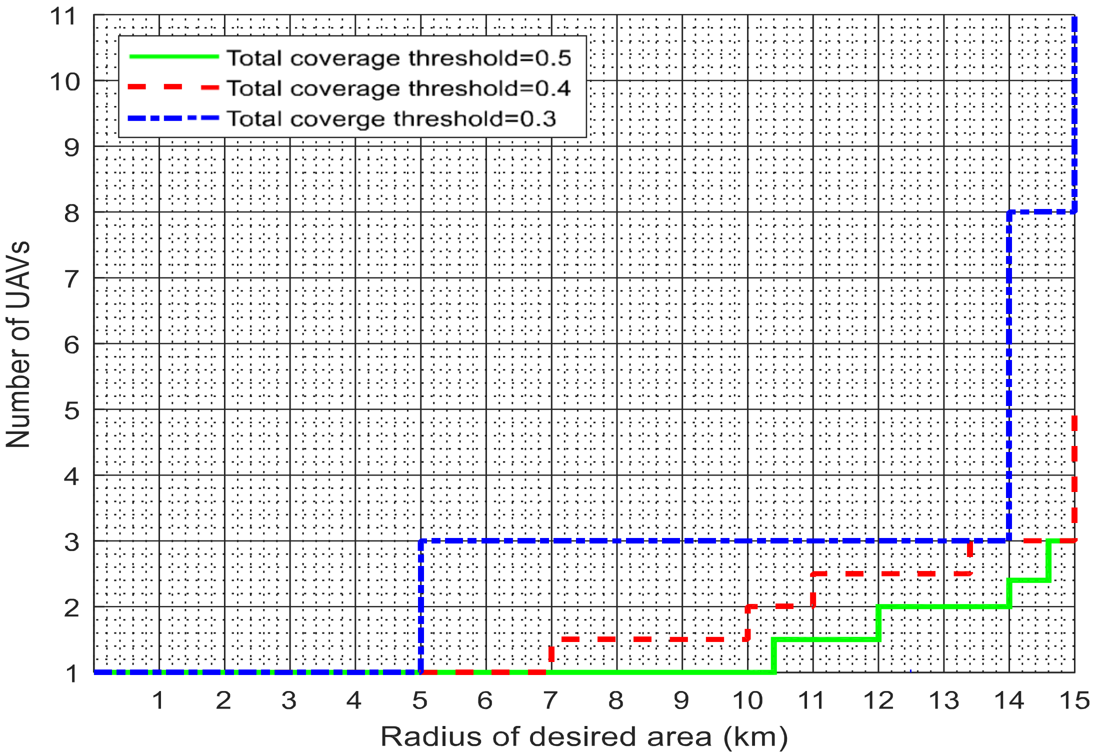

Figure 4.4: Figure showing the number of required UAVs required to cover the desired area

Figure 6 shows the minimum required number of UAVs to give coverage in the given desired area. The coverage threshold corresponds to the minimum portion of the given area which needs to be covered by the UAVs.

To satisfy at least 0.3 coverage requirements with maximum coverage lifetime, either one UAV or more than two UAVs are required

In conclusion as the size of the desired area increases, more UAVs are needed to meet the coverage requirement.

## 4.5 Comparison of Overlapped Proposed and Non-Overlapped Systems

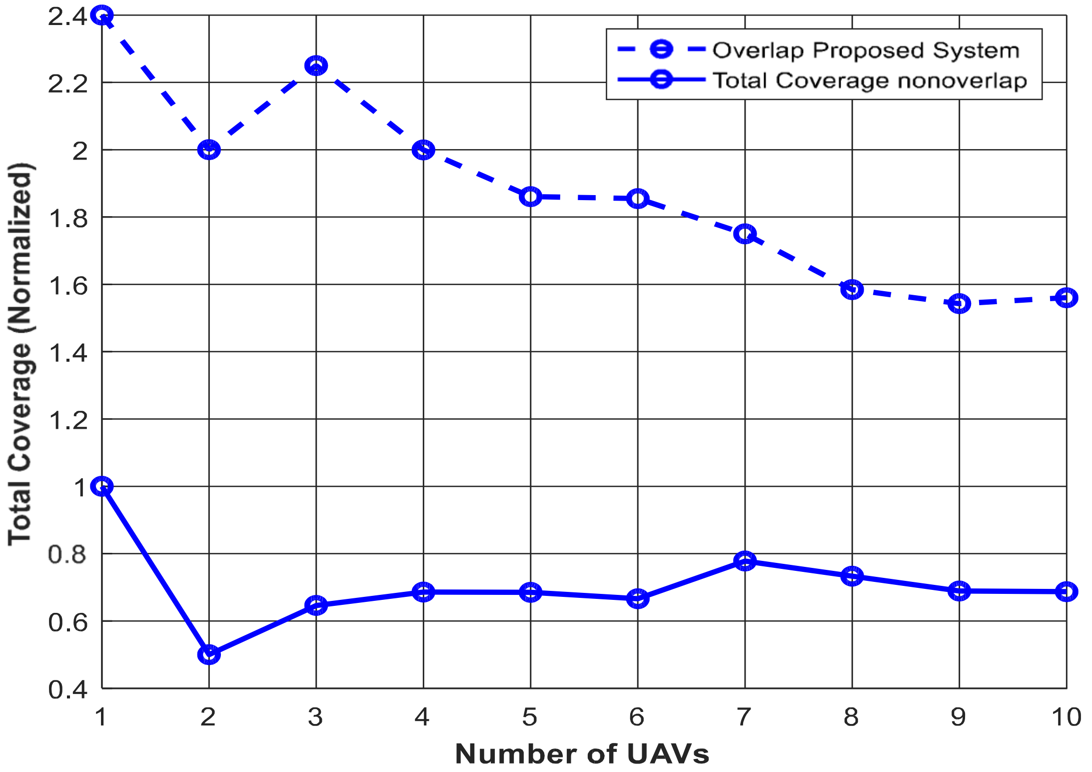

Figure 4.5: Figure showing the comparison of overlapped proposed and non-overlapped systems

In this research, we have learned that using overlapped circles requires a smaller number of UAVs to provide maximum coverage to the desired area or desired users than non-overlapped circles. Overlapped circles give a good coverage lifetime with fewer UAVs than non-overlapped circles.

The results have shown that UAV altitude and position is based on the antenna beamwidth and the number of UAVs.The number of UAVs to be deployed depends on the size of the desired area to be covered

# Chapter 5

## 5 Challenges, recommendations, and conclusion

Overlapped circles require a fewer number of UAVs to provide maximum coverage to the desired area or desired users than non-overlapped circles

### 5.1 Challenges

The greatest challenge is about the battery life of the quadrotor UAVs that only spend 30-40 minutes up to provide coverage which is a very small time in case there is a malfunctioning terrestrial base station because it might take hours to fix a malfunctioning terrestrial base station.

We also faced a challenge to get access to MTN company engineers to give us an over of when the base station has a malfunction and the time, they take to fix the malfunction

There are a lot of interferences associated with an overlapped system leading to low quality of service and also solving some equations was challenging due to the high number of unknowns and the nonlinear constraints.

### 5.2 Recommendations

To deploy a minimum number of UAVs to achieve a maximum total coverage density while achieving a maximum coverage lifetime, the overlapped UAV deployment system should be used or considered.

### 5.3 Conclusion

In this research, we have learned that using overlapped circles requires a fewer number of UAVs to provide maximum coverage to the desired area or desired users than non overlapped circles, and overlapped circles give a good coverage lifetime with fewer UAVs than non overlapped circles.

The results have shown that UAV altitude and position are based on the antenna beamwidth and the number of UAVs and the number of UAVs to be deployed depends on the size of the desired area to be covered.

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