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MASTER'S THESIS

POSITIONING OF MULTIPLE UNMANNED AERIAL VEHICLE BASE STATIONS IN FUTURE WIRELESS NETWORK

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ABSTRACT

Unmanned aerial vehicle (UAV) base stations (BSs) can be a reliable and efficient alternative to full fill the coverage and capacity requirements when the backbone network fails to provide the requirements during temporary events and after disasters. In this thesis, we consider three-dimensional deployment of multiple UAV-BSs in a millimeter-Wave network. Initially, we defined a set of locations for a UAV-BS to be deployed inside a cell, then possible combinations of predefined locations for multiple UAV-BSs are determined and assumed that users have fixed locations. We developed a novel algorithm to find the feasible positions from the predefined locations of multiple UAVs subject to a signal-to-interference-plus-noise ratio (SINR) constraint of every associated user to guarantees the quality-of-service (QoS), UAV-BS's limited hovering altitude constraint and restricted operating zone because of regulation policies. Further, we take into consideration the millimeter-wave transmission and multi-antenna techniques to generate directional beams to serve the users in a cell.

We cast the positioning problem as an ℓ_0 minimization problem. This is a combinatorial, NP-hard, and finding the optimum solution is not tractable by exhaustive search. Therefore, we focused on the sub-optimal algorithm to find a feasible solution. We approximate the ℓ_0 minimization problem as non-combinatorial ℓ_1-norm problem. The simulation results reveal that, with millimeter-wave transmission the positioning of the UAV-BS while satisfying the constrains is feasible. Further, the analysis shows that the proposed algorithm achieves a near-optimal location to deploy multiple UVA-BS simultaneously.

Keywords: UAV Communication, Positioning, UAV base station, beamforming, mmWave, Convex Optimization, ℓ_0 minimization.

TABLE OF CONTENTS

FOREWORD

This thesis absorbed on the Positioning of Multiple Unmanned Aerial Vehicle Base Stations (UAV-BS) in the future Wireless Network. This thesis was funded at Center for Wireless Communications (CWC) of University of Oulu, Finland. Here I am using this opportunity to express my gratitude to my Thesis advisor, Supervisor, and Mentor Prof. Premanandana Rajatheva, who supported me and guide me throughout the course of this master thesis. He dependably allowed this thesis to be my own but directed me in the right direction whenever I required it. I am thankful to Academy Prof. Matti Latva-aho and Dr. Pekka Pirinen for their support during my research. I am also grateful to Matti Isohookana, for his support and guidance throughout the period. I would like to thank Dr.Maheshi B.Dissanayake, University of Peradeniya, Sri Lanka and my technical advisor Dr.K.B.Shashika Manosha. Without their involvement and valuable comments, the validation could not be successful. Also, I would like to thank all the lecturers from University of Peradeniya for their support and guidance. Finally, I must express my thankfulness to my parents and my friends for providing me with motivations and continuous encouragement throughout my research work and the degree period. This achievement is not possible without them. Thank you

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LIST OF ABBREVIATIONS AND SYMBOLS[1]

Acronyms

3D	Three Dimensional
3GPP	Third Generation Partnership Project
4G	Fourth Generation
4K	Four times the pixel resolution
5G	Fifth Generation
A2G	Air to Ground
AoD	Angle of Departure
AR	Augmented Reality
AT&T	American Multinational Conglomerate Holding Company
AWGN	Additive White Gaussian Noise
BS	Base Station
CDMA	Code Division Multiple Access
COW	Cell On the Wing
CVX	Convex
D2D	Device to Device
DL	Downlink
EDGE	Enhanced Data Rates for Global Evolution
EE	Everything Everywhere
EPG	Exact Potentail Game
eMTC	enhanced Machine-Type Communication
FR	Floating Relay
GA	Genetic Algorithm
Gbps	Gigabits per second
GPRS	General Packet Radio Service
GSM	Global System for Mobile
eMBB	enhanced Mobile Broad Band
HAP	High Altitude Platform
HSPA	High speed Packet Access
KPI	Key Performance Indicator
IoT	Internet of Things
ITU	International Telecommunication Union
LAP	Low Altitude Platform
LoS	Line of Sight
LTE	Long Term Evolution
MANETS	Mobile Ad Hoc Network
MISO	Multiple Input Single Output
mMTC	massive Machine-Type Communication
MS	Mobile Station
NE	Nash Equilibrium
NLoS	Non Line of Sight
NP	Nondeterministic Polynomial time
NR	New Radio
OFDM	Orthogonal Frequency-Division Multiplexing

QOE	Quality of Experience
QoS	Quality of Service
SE	Spectral Efficiency
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
TDD	Time Division Duplex
UAV	Unmanned Aerial Vehicles
UMTS	Universal Mobile Telecommunications System
UE	User Equipment
URLLC	Ultra Low Latency Communication
V2V	Vehicle to Vehicle
VLC	Visual Light Communication
VR	Virtual Reality
WCDMA	Wideband Code Division Multiple Access
xMBB	Extreme Mobile Broad Band

Symbols

n_k	Additive white Gaussian noise
$\theta_{k,p}$	Angle-of-departure of the p-th path
M	Antenna spacing
$\mathcal{CN}$	Complex Gaussian distribution
$h^l_{j,k}$	Channel vector between kth user and lth UAV-BS
d^j_k	Distance between the serving UAV-BS j and the user k
$\alpha_{k,p}$	Gain of p-th path
L_D	Location matrix
$\mathbf{S}$	Location matrix
h_{min}	Minimum flying height of the UAV-BS
h_{max}	Maximum flying height of the UAV-BS
N	Number of transmit antennas
N_p	Number of multi-paths
c	Number of Combinations
N_{pd}	Number of predefined locations inside each square
γ	Path loss exponent
$\mathbf{r}_{j,k}$	Received signal of the kth user of jth UAV-BS
$s_{j,k}$	Scalar data symbol sent from jth UAV-BS to kth user
$\Gamma_{j,k}$	Signal-to-interference-plus-noise ratio (SINR) of the kth user
$\mathbf{w}_{j,k}$	Spatial directivity of the signal sent from jth UAV-BS to user k
$\mathbf{L}$	SINR matrix
$\mathcal{D}$	Set of UAV-BSs
$\mathbb{R}$	Set of real numbers
$\mathcal{U}_j$	Set of all single antenna users associated with jth UAV-BS
$p_{j,k}$	Transmit powers from jth UAV-BS to kth user
τ	Vector of all UAV-BS positions for a combination
Γ	Vector of all user SINR values for a combination
ζ	Wavelength of the carrier frequency

Operators

$\|\cdot\|$	Absolute value
$\sum$	Summation operation

1 INTRODUCTION

Wireless communication is one of the unavoidable factors in technology evolution of human life. Commercial wireless systems improve the connectivity between humans and devices. While providing the massive connection between mobile phones, laptops, sensors, and actuators, there will be a requirement of providing high quality and uninterrupted services to users. When considering the rapid development from the first generation analog-based cellular deployment to fifth generation (5G) new radio (NR), the challenges still exist in more complex forms. Next-generation 5G system is going to be implemented with enhanced mobile broadband(eMBB), ultra-reliable low-latency communication (URLLC), and massive machine type communication (mMTC).

The term eMBB is the evolved version of current fourth generation (4G) mobile broad band (MBB) which is going to provide much faster data rates and better user experience than the current technology. The eMBB services will include 360^0 video streaming, real-time traffic alerts, real-time three-dimensional (3D) 4K video games, autonomous vehicle network with advanced features as well [1]. It is going to have three major distinct attributes. Those are higher capacity, enhanced connectivity, and higher user mobility. URLLC is going to serve latency-sensitive applications such as factory automation, autonomous vehicle-based driving, and remote surgery. Therefore the network should guarantee the latency of 1ms or less and an error below 1 packet loss in 10^5 packets [2]. URLLC needs a higher Quality of Service (QoS) than other applications since it is working with instantaneous and intelligent systems. mMTC provides scalable and efficient connectivity for a massive number of low cost and low power devices which normally need a small amount of data and infrequent transmission. This narrowband internet access is useful for sensing, metering, and monitoring devices in wireless sensor networks, smart homes, smart cities, etc. This network is designed to be scalable for the future addition of new devices.

According to the above-mentioned scenarios and applications, improving network robustness with efficient use of available resources and mitigating the interference effects in the wireless communication system is essential. Furthermore, we cannot avoid sudden emergencies such as natural disasters, unplanned power outages, and unusual wireless traffic demands. During such instances, we need a solution that can be implemented with less infrastructure and rapid deployment. Furthermore, the solution should be able to provide the demand for pre-planned events such as sports events, musical festivals and pre-disaster awareness events as well.

All service providers are expected to deliver a good quality of service. Customer satisfaction is one of the important indicators that shows the capability of the service provider. It has been suggested that Quality of Experience (QoE) should also be considered as a measure like QoS in wireless communication in the 5G era [3]. Also, QoE is the real expectation from the user's point of view and may differ from the service provider's perspectives. Therefore, service providers have a high responsibility to provide good quality and uninterrupted services than merely providing the primary services. Also there is an additional liability to provide services during critical situations. In the recent past, many companies have started to invest in disaster management communication strategies [4]. However, collectively, there is a gap in technology to manage critical situations.

In recent past, unmanned aerial vehicles (UAVs) have grabbed the attention in many fields of studies because of their flexible attributes such as adaptive altitude, flexibility in design and movement, and mobility [5]. It can be used as a relay to enhance coverage, capacity, and energy efficiency in wireless communication. On the other hand, using them as base stations is also an emerging topic. Drone base station, which is known as unmanned aerial vehicle base station (UAV-BS) is a new form of application of drones which is so far used in the military for reconnaissance purposes. Here the name of UAV-BS denotes all different types of base stations that are mounted on a UAV or drone or flying platform which has the ability to change their altitude, avoid obstacles and establish the line-of-sight (LoS) between users. UAV-BS can be a cost-effective and efficient solution for the challenging scenarios discussed earlier such as natural disasters, unplanned power outages, etc. [6–8]. For example, after the hurricane Maria, AT&T had deployed UAV based cell on the wing (COW) to provide long-term evolution (LTE) network coverage for voice, data and text services to their users around a 40-square mile area in Puerto Rico [4]. Nokia and EE are providing their UAV-BS services in Scotland since 2016 to manage the LTE coverage gap during the disaster periods [9]. Ericsson has started to provide on-demand based coverage for special events like music festivals via UAV-BS [9]. In addition, UAV-BS will be more beneficial in high-density urban areas where it is impossible to deploy a cellular base station due to land scarcity and high installation and maintenance costs. Therefore, UAV-BS can be used as a cost-effective solution for telecommunication service provides.

However, there are some key challenges to the usage of the UAVs such as 3D deployment in the airspace, air to ground channel modeling, network planning, flying time optimization, handover, battery life of the UAV, and performance analysis [5]. In addition, we need to take into account the regulations as well. Those concerns are, privacy, security, public safety, collision, and data protection. As stated in [5], according to the flying altitude UAVs can be classified into two categories, high altitude platforms (HAPs) and low altitude platforms (LAPs). HAPs are the UAVs which fly over 17 km and LAPs normally fly around few meters, maximum up to 1 km. According to the aviation regulations in different countries, different countries have different allowable flying altitudes as minimum distance to people and maximum distance to the airports. In addition, there are some areas that UAVs cannot operate due to government restrictions.

In our study, we have taken into account above mentioned issues. The proposed algorithm has user SINR constraint, restricted zone constraint and hovering altitude constraint.

1.1 Thesis Contribution

The work is carried out under the topic positioning of multiple unmanned aerial vehicle base stations in future wireless networks, to find the optimum locations of the UAV-BSs in order to achieve a high spectral efficiency and a better user experience.

The multi-cell UAV-BS model consists of D number of UAV base stations each equipped with N number of antennas. Each cell user is associated with a single UAV-BS and the user distribution is assumed to be uniform. We assume that there is no impact on UAV-BS downlink transmission due to orientation drifts. Our goal is to find the possible optimum locations for the UAV-BS in order to achieve the user quality of service-related parameters. In addition, we have considered the height and restricted regions as well for the positioning.

1.2 Thesis Outline

The rest of this thesis is organized as follows:

- **Chapter 2:** Includes the concepts, theoretical background, summary of previous studies and proposals need for our research.
- **Chapter 3:** The overall components of this study are provided. It consists of the system model, optimization problem formulation and methods for solution approach.
- **Chapter 4:** The outcomes of this study is elaborated in this chapter. Different simulation scenarios, assumptions, and simulation parameters are presented.
- **Chapter 5:** The contribution of our study is concluded in this chapter.

2 BACKGROUND

This chapter describes the concepts related to our research and detailed literature survey about UAV communication and optimal deployment scenarios. Positioning the UAV-BS in a optimal location still remains a challenge. Therefore, to develop a proper algorithm to solve the positioning problem is a major requirement. For example, in emergency situations we have to work with a limited number of resources, thus have to get the maximum benefit out of the available resources. Achieving high spectral efficiency (SE) becomes a major problem while maintaining the key performance indicators (KPI). As mentioned above, the demand during critical situations is higher than the average demand or usage. Therefore, the placement of UAV-BSs will become the major factor in resource allocation and quality management. On the other hand, in pre-planned situations we have the freedom of using many numbers of UAVs, but there is a requirement to provide the full coverage to the users. Even though our requirement is to provide the full coverage to the particular geographical area, it is not desirable to waste the resources. Furthermore, an excessive amount of UAV deployment will create interference issues which lead to degradation of user experience.

2.1 Wireless Communication in 5G NR

Over the last 40 years, human beings have witnessed the developing story from the first generation (1G) of mobile communication to the 5G new radio. The 1G of mobile communication was introduced in the period of the 1980s which was based on analog transmission. It provided only the voice services. Then the digital era of communication was introduced in the early 1990s as second generation (2G) mobile communication. Even though the transmission was digital, it was also only able to provide the voice services. Later, general packet radio service (GPRS), which has a maximum throughput of 50 kbit/s, global system for communication (GSM), and enhanced data rates for GSM evolution (EDGE) which has a maximum throughput of 1 Mbit/s were introduced. However, the requirement for throughput and capacity were not satisfied. The third generation (3G) of mobile communication was introduced at the start of 2000. It provided the real flavour of the internet and high-quality mobile broadband. In 2001, universal mobile telecommunications service (UMTS) was introduced and wideband code division multiple access (WCDMA), high-speed packet access (HSPA) and HSPA-plus were also introduced through the 3G development.

LTE technology, the 4G of mobile communication was introduced in 2010 with high end-user throughput. Orthogonal frequency-division multiplexing (OFDM) based transmission and multi-antenna based designs provided a wider transmission bandwidth. Furthermore, LTE technology supports operation in the paired and unpaired spectrums. That means LTE works in both frequency division duplex (FDD) and time division duplex (TDD). Recent advances in applications such as 4K video streaming, online games, autonomous vehicles, remote medical applications have created a huge amount of traffic in the network. There is a requirement of high throughput and low latency to fulfill the needs created by those applications. A new technological advancement is thus needed to satisfy the above requirements. The comparison between 4G and 5G described in Figure 2.1. 5G network is going to be a breakthrough in wireless communication with eMBB,

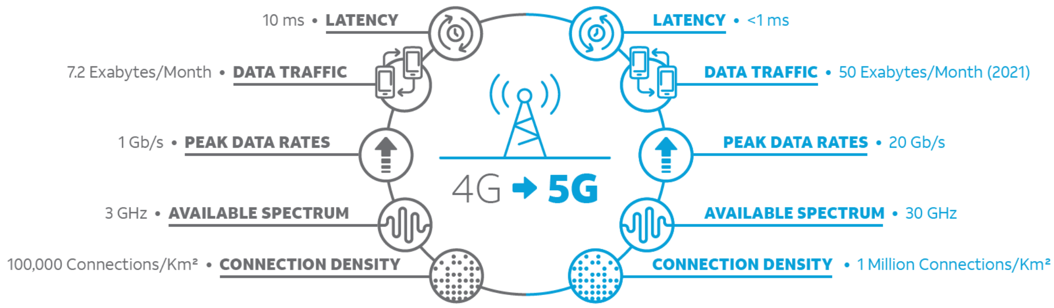

Figure 2.1. Comparison between 4G and 5G [10].

URLLC, and mMTC. As expected, 5G is going to deliver 10 Gbps peak throughput, 1ms or lesser latency and 1 packet loss in 10^5 packets.

Although 5G fulfills the current requirements, there will be more advancements in communication technologies beyond 5G. The sixth generation (6G) mobile communication will bring solutions to the challenges and technology gaps faced in 5G. Requirements may arise for holographic communications, high precision manufacturing, artificial intelligence, etc. [11]. The 6G communication is expected to utilize on sub-THz or visible light communications (VLC) with 3D beamforming to provide network access according to the geographical variations and demand [11].

2.1.1 5G Use Cases

In this section, the major 5G use cases and the requirements to fulfill the use cases are discussed. There is a collection of use cases which creates challenges to 5G. Some of the main areas for use cases are agriculture, automotive, construction, energy, finance, health, manufacturing, media, public safety, transport, retail, and consumer. Figure 2.2 illustrates different 5G use cases with their frequency spectrum and requirements.

Autonomous vehicle and control are one of the trending areas, which will provide numerous benefits to humans such as accident avoidance, efficient traveling time and stress-free life [12]. Vehicle-to-vehicle, vehicle-to-people, and vehicle-to-sensors communications are introduced as enabling technologies to facilitate autonomous driving. Therefore, 5G needs to provide low latency and highly reliable communication. On another aspect, having a reliable network during an emergency situation has a major role to rescue people and save their lives. In such application, availability and energy efficiency are the crucial requirements. The factory automation and industrial manufacturing processes need to have low latency and highly reliable communication to support life-critical applications [13].

High-speed trains are another domain for communication requirement. People need internet access while they are traveling at high speed. Therefore there is a requirement for user throughput and end-to-end latency to satisfy the user requirements during the on-board time for their travelling via the high-speed train [15]. Some outdoor large-

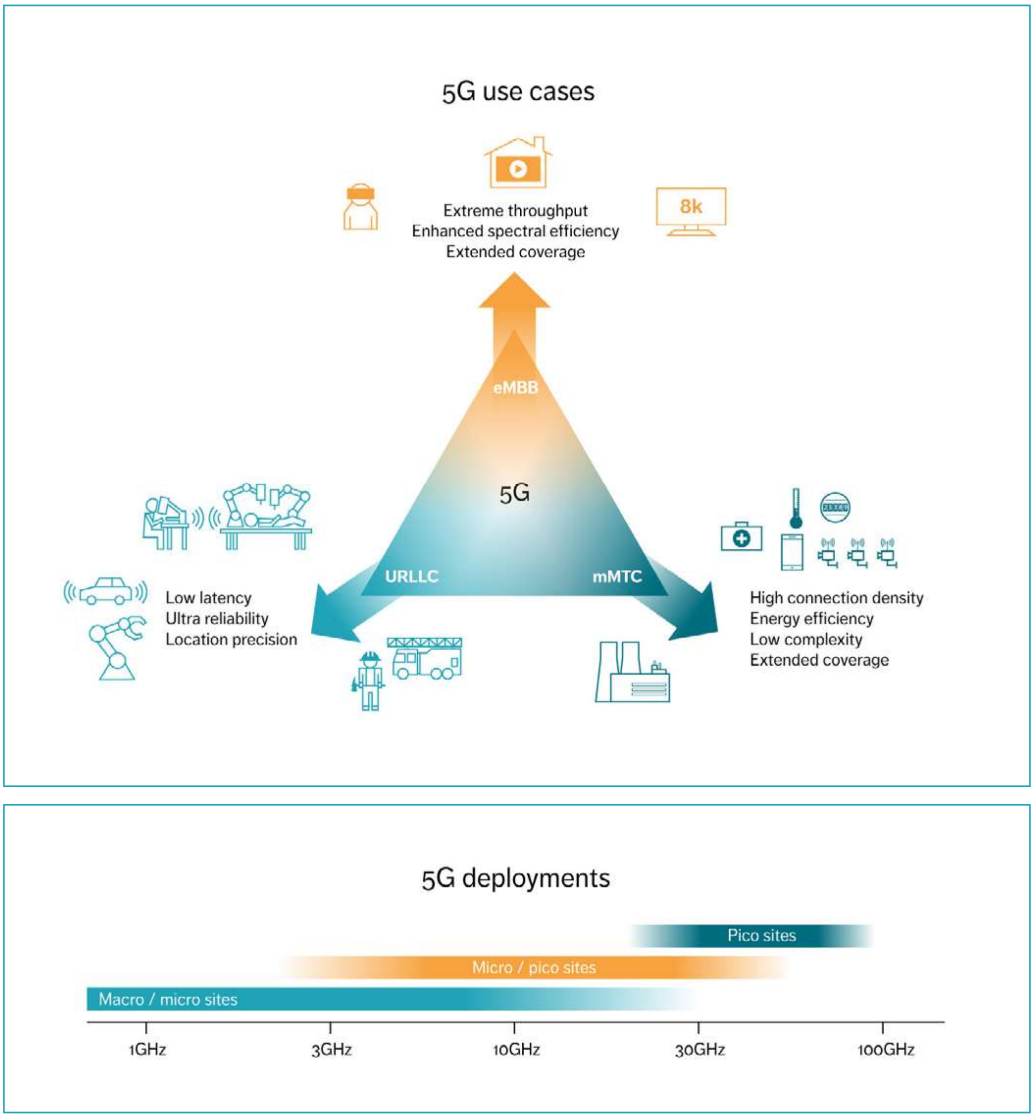

Figure 2.2. 5G Use cases, spectrum and deployments [14].

scale events create a huge amount of data usage. For example, there can be instances where the crowd taking high-resolution captures and sharing them with their network. Therefore, 5G needs to provide excellent user experience, which means high throughput and lower outage probability. Another domain is for data collection. There are some applications like surveillance, critical monitoring and information sharing which need efficient transmission to communicate with relevant nodes to complete the process. Apart from all, every single person has a different requirement and content for their entertainment. Therefore, significantly high data rates and excellent user experience are the main concerns in such entertainment applications. In addition, low latency is also required to avoid interruptions.

The smart health systems are going to do a revolution in the health section which includes remote surgeries and eAmbulance [16]. In such life-critical applications, ultra-reliable communication and very low end-to-end latency are the main requirements. Additionally, large shopping malls and smart cities also create many different requirements to be fulfilled by 5G. High availability of connections for safety and security, high user throughput and low latency are the requirements in such scenarios. Smart logistics is going to manage the traffic efficiently reducing the fuel consumption. In order to achieve that, 5G needs to provide high data rate and low latency [17].

The smart grid is going to interconnect all electricity, water and gas production, distribution and their usage together. A failure or blackout in these areas may create a critical impact on usual activities. Hence, wireless communication plays a vital role in monitoring and controlling the smart grids. The teleprotection related applications need very low latency and high reliability. Virtual reality (VR) and augmented reality (AR) based applications create new dimensions of life experience. There also 5G has the requirements to provide a very high data rate and tight latency to ensure the performance of AR and VR applications [18].

2.1.2 5G Requirements

In Section 2.1.1, we presented a summary of use cases for 5G in different areas and domains. In order to fulfill those requirements 5G needs to maintain several key performance indicators (KPI). The KPIs are availability, connection density, cost, energy consumption, experienced user throughput, latency, reliability, security, and traffic volume density [16].

- **Availability**

  It is defined as the percentage of communication links or users in a certain geographical area, with a satisfied the QoS or experience levels.

- **Connection density**

  The number of simultaneously active users or devices divided by the area, in a considered area during a predefined time span.

- **Cost**

  The total cost need for an operator to deploy the network which is proportional to the number of base stations or nodes, the number of user devices and the available spectrum.

- **Energy consumption**

  It is defined as energy per information bit and power per unit area.

- **Experienced user throughput**

  In a predefined time span, the total amount of data traffic a user achieves divided by the time period.

- **Latency**

  Latency is defined in two different ways, one-trip time (OTT) latency and round-trip time (RTT) latency. OTT is the time required to send a data packet from the transmitter to the receiver. RTT is defined as the total time taken for the transmitter to send the data to the receiver and to receive the acknowledgement from the receiver.

- **Reliability**

  It is the probability of a certain amount of message or data sent from transmitter to receiver successfully.

- **Security**

  Security is one of the important factors, but is hard to measure. In generally it measures the time taken for a skilled hacker to access the data.

- **Traffic volume density**

  In a predefined time span, the amount of traffic transferred by all the devices divided by the area size.

2.1.3 5G System Concept

5G has a very wide range of requirements than in previous generations of communication. Therefore, 5G systems need different combinations of technologies and services. There are three generic 5G services which are defined as extreme mobile broadBand(xMBB), massive machine-type communication(mMTC) and ultra-reliable machine-type communication(uMTC) [16]. All individual use cases are combinations of these three services.

- **extreme Mobile BroadBand (xMBB)**

  It provides high data rate, low latency, and extreme coverage. It can support around 50 Mbps to 100 Mbps. Some of the main solutions of xMBB are new spectrum and a new type of spectrum access which include centimeter-wave and millimeter-wave communication, new radio interface for dense deployment, spectral efficiency, advanced antenna technologies, and the support for user mobility.

- **massive Machine-Type Communication (mMTC)**

  mMTC provides wireless services to a lot of customers, scalable connectivity and efficient transmission. This approach supports cost and energy-constrained devices which are used for data collection based applications. There are three different mMTC access types used for different types of applications. Direct network access (MTC-D), access via an aggregation node (MTC-A) and short-range device-to-device access (MTC-M) are the three cases.

- **ultra-reliable Machine-Type Communication (uMTC)**

  This provides very low latency communication to the users. This approach is a major concern for vehicular networks and manufacturing automation. Fast communication setup, low latency, establishing reliable communication, high system availability, and mobility are the challenges to achieve the uMTC.

2.2 Internet of Things

Internet of Things (IoT) based applications add value to our lives incorporating with the internet and sensors. It is an embedded system based platform, where a large amount of data is generated and transferred. It makes human life easier and smarter. Collectively, these IoT applications connect the massive amounts of objects and devices with intelligence in several domains, such as smart home, health care, agriculture, industries, wearable devices, etc. IoT based approach is initiated with creating an idea, sensing the data from the environment, analysing the data, system development finally connecting the devices or objects. A brief overview of IoT applications and related domains is illustrated in Figure 2.3.

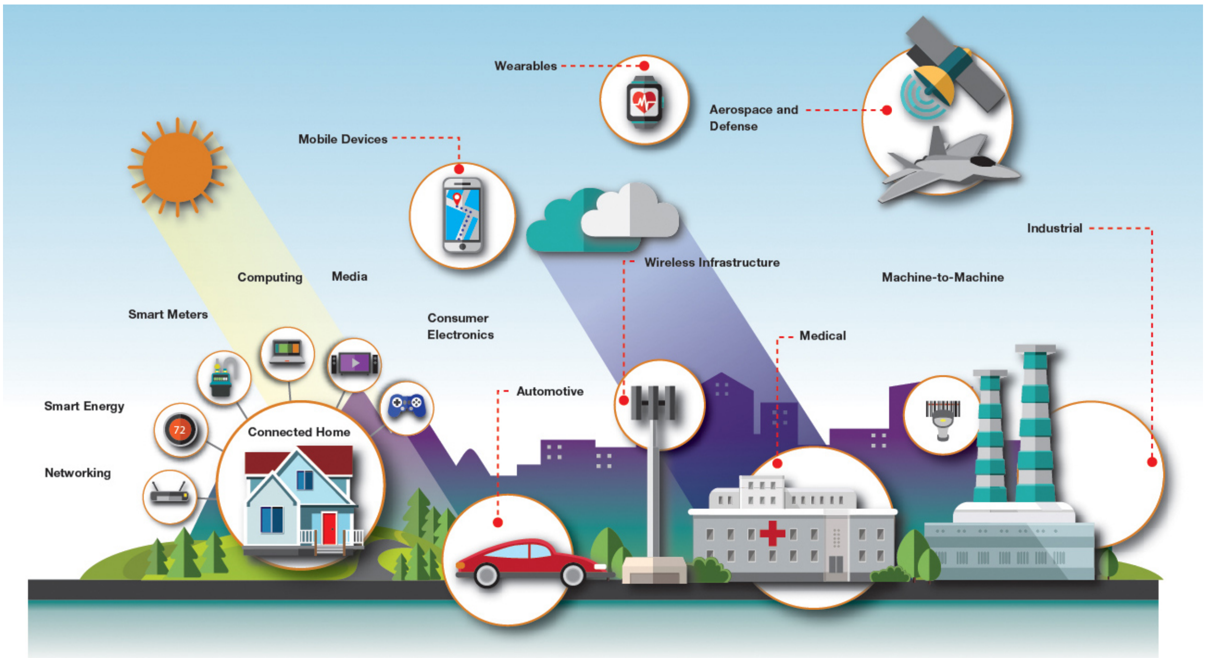

Figure 2.3. Schematic of the IoT based applications [19].

In the IoT domain, UAVs have a big role to establish the applications in different domains. As discussed in [20], the reliable and efficient transportation system in smart cities can be developed to incorporate with UAVs. Apart from the roadside unit, UAV can establish communication with a mobility service center via device-to-device (D2D) multi-hop communication to control the traffic and to alarm during accidents. In addition, Amazon and Walmart [7] have been working on UAV based shipment delivery as well. Furthermore, public safety communication in UAV assisted heterogeneous networks are discussed in [7]. Collectively, UAV based IoT applications are expected to fulfill future requirements in different application areas.

2.3 Millimeter-wave Communication

2.3.1 Millimeter-wave Spectrum and Channel Propagation

Next-generation wireless communication, namely 5G, is going to operate in the existing 4G-LTE frequency and mmWave bands. The ranges of the frequencies are 600 MHz to 6 GHz and 24 GHz to 86 GHz respectively [21]. The major advantage of this frequency range is the ability to get multi-gigabit data rates because of the available large bandwidth. However, there will be a challenge to make reliable communication due to the stern propagation environment and blockages [22]. The reason for this is that the propagation loss is proportional to the square of the carrier frequency and the commonly available environmental materials can make blockages such as the human body, brick, and mortar. Therefore, there is a major requirement for mmWave channel modelling. According to [22], the major characteristics of the mmWave which are going to make the impact on wireless communications are; the propagation difference between LoS and non-line-of-sight (NLoS) paths, higher penetration loss than in sub-6GHz frequencies, angular domain sparsity and small scale fading impact reduction. As proposed in [22], by directional antennas the propagation related issues can be solved. Due to the smaller wavelength, a particular area can be covered by massive antenna elements. Therefore, there is a possibility to increase the link budget with beamforming techniques. The blockage effect can be reduced by ultra-dense deployment. Therefore, the outage probability can be reduced [23].

2.3.2 Beamforming

Millimeter-wave band communication will create new challenges such as large scale losses, attenuation, and coupling loss. Free space losses can be compensated by high-gain antennas at the transmitter and the receiver. Also, beamforming using adaptive antennas and higher order sectorization establish reliable and communication using mmWaves.

Beamforming Architecture

In large antenna arrays, if antenna array is implemented as a phase-array, it can electrically steer the direction of the beam, which forms a beam to serve users. There are three beamforming architectures proposed; digital beamforming, analog beamforming, and hybrid beamforming, which are illustrated in Figure 2.4.

As shown in Figure 2.4(a), digital beamformers with several antennas are more power consuming and complex. Therefore, in the application point of view, they are infeasible. In mmWave communication, analog or hybrid beamformers are expected to use. An analog beamforming network generates physical beams and does not create complex beamforming patterns. Therefore, it may create interference in multi-user scenarios [16]. Hybrid beamformers are a compromise between analog and digital beamformers.

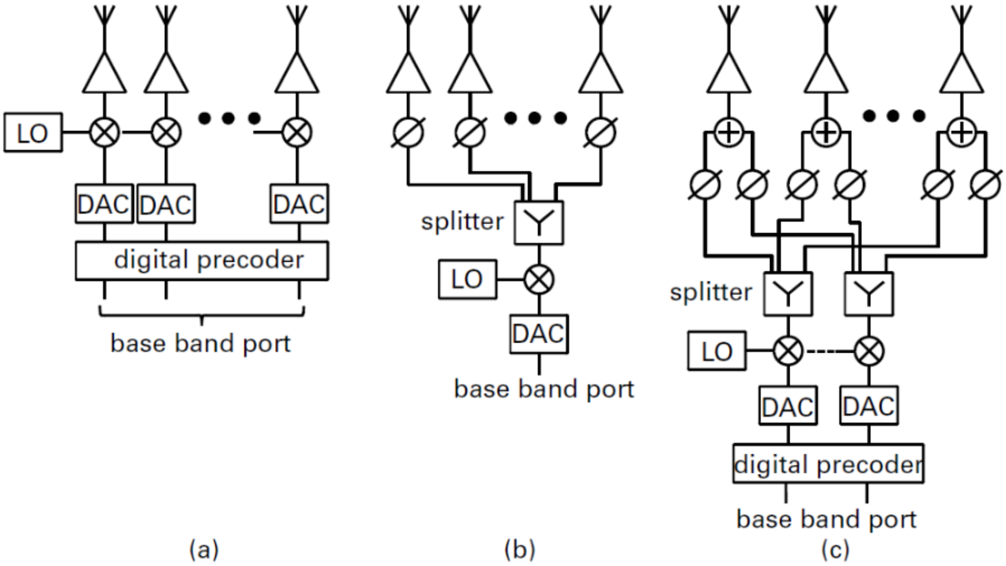

Figure 2.4. Beamforming architectures (a) digital (b) analog (c) hybrid [16].

2.4 Unmanned Aerial Vehicles

2.4.1 UAV Classifications

The selection of an appropriate UAV for a given type of application plays a major role in Capex optimization. Flying height of a UAV is an important feature in wireless communication-related applications. UAVs can be categorized based on hovering altitude, weight, wing type, size etc. Since our requirement is for height, we can classify them as high altitude platforms (HAPs) and low altitude platforms (LAPs). In general, the UAVs which can fly over 17 km falls under the category of HAPs and the UAVs which can fly only a few meters maximum up to 1 km are categorized as LAPs. LAPs can move quickly and flexibly than HAPs [5]. HAPs are mostly used in wide-scale coverage requirement scenarios and LAPs are normally used for data collection. Figure 2.5 elaborates on the different types of UAVs and their attributes.

2.4.2 UAV Regulations

Regulations and policies are prominent factors when planning the UAV deployment in a commercial network. As stated in [5], there are several factors included in the regulation decision, such as privacy of the public users, public safety, security issues, data protection, and collision of the UAVs. Therefore the regulations are continuously analyzed and renovated. These regulations are mostly decided based on UAV type, working spectrum, hovering altitude and flying speed. In summary, the regulations are developed under five important categories as mentioned in [5, 24]. Those are applicability, operational limitations, administrative procedures, technical requirements and implementation of ethical constraints. We note that UAV regulations are different from one country or region

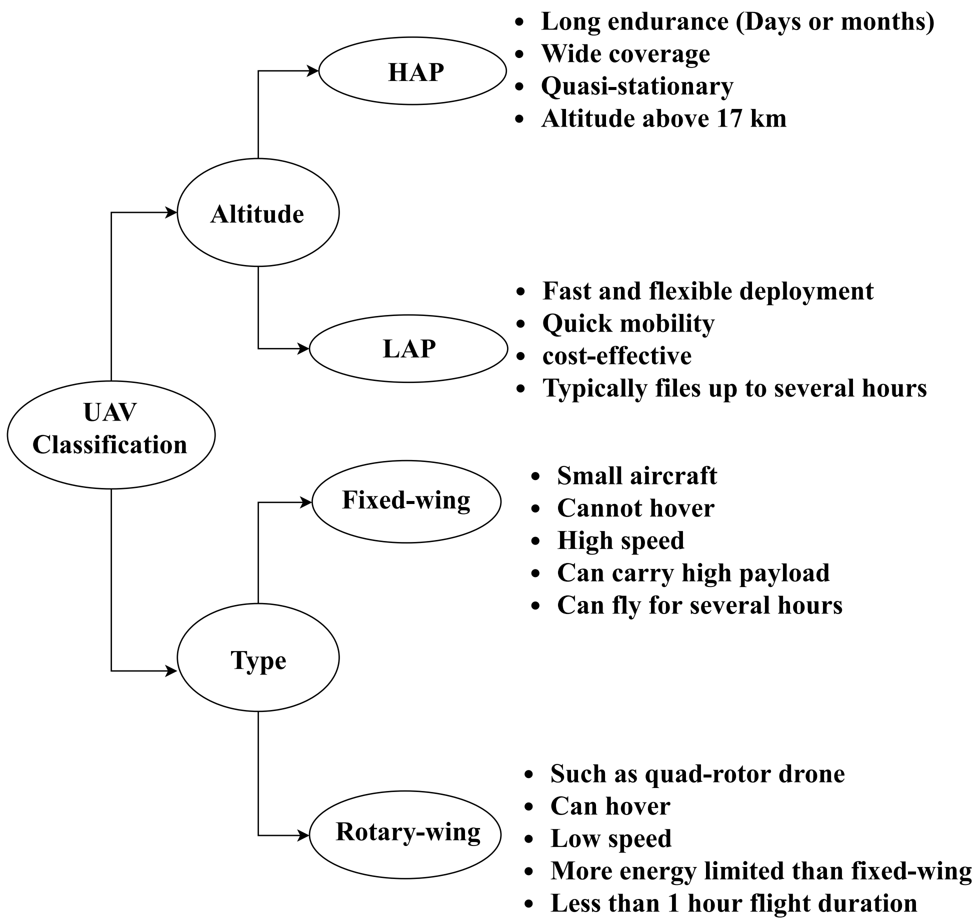

Figure 2.5. UAV Classification [5].

to another. Therefore, the design constraints are needed to be analysed accordingly. We have listed the UAV regulations in five different countries in Table 2.1 below.

Table 2.1. UAV Regulations in different countries [5].

Country	Max altitude	Min distance to people	Max distance to airport
US	122 m	N/A	8 km
Australia	120 m	30 m	5.5 km
South Africa	46 m	50 m	10 km
UK	122 m	50 m	N/A
Chile	130 m	36 m	N/A

2.4.3 UAV Use Cases

This section discusses the prospective applications of UAVs in the wireless domain. The use cases are public safety scenarios, hotspots, UAV caching applications, and IoT nodes. UAV base stations can be a complementary solution to fulfill the current network issues. LAP-UAV deployment can be a cost-effective and quick solution to provide wireless connectivity. Small cell deployments by LAP-UAVs for temporary events are also more economically beneficial than traditional base station deployments for such events. Meanwhile, deployment of HAP-UAV can be a long term solution in less populated rural areas [5]. UAV-BSs can provide a compatible solution for ultra-dense small cell networks. In mmWave communication, UAV-BS can establish a LoS link between the user device and the BS which can provide the high capacity to the user. In vehicular networks, UAV-BS can establish a reliable communication between vehicle-to-vehicle (V2V) and D2D by using transmit diversity. Because of the three dimensional deployment, UAV-BSs can have more freedom to optimize and dynamically provide coverage and capacity.

Public safety-related communication during and after disasters such as floods, hurricanes, tornadoes, and snowstorms plays an important role in a mobile operator. There is a high probability of damage in terrestrial communication during the disaster. In such scenarios, there is a huge need for communication for rescue operations and awareness. Therefore, we need a promising solution to handle these kind of critical situations. UAV-BSs can establish the deployment in a short time with low cost. In addition, they can provide on-demand communication as well. Providing broadband connectivity by UAV-BSs is more efficient. Collectively, UAV-BS can be an appropriate solution for public safety scenarios [5].

UAV-BSs can be used for information dissemination and coverage enhancement for D2D and V2V networks. UAVs can easily move around and establish the LoS between ground devices. D2D network performance is limited because of the interference among the devices and short-range of communication. In these scenarios, UAV-BSs can accelerate the performance by intelligently broadcasting the information to ground devices. This is mostly suitable for emergency messaging or alerting for public safety-related situations. In addition, UAV-BSs can improve the reliability of the V2V network by spreading safety information among the ground vehicles. Furthemore, in both cases UAV-BSs can establish the transmit diversity to enhance the performance.

Massive multiple-input and multiple-output (MIMO), 3D MIMO, and mmWave communication can be improved by using UAV-BSs because of their aerial positioning and on-demand deployment. UAV-BSs can establish 3D beamforming while minimizing inter-cell interference. Compared to traditional beamforming, 3D beamformer [25] can support a large number of users and improve system throughput. Therefore, when 3D beamforming is incorporated with UAV-BSs, there is a high possibility to improve user experience and spectral efficiency. Further, UAV based antenna array elements efficiently provide services to ground users. By adjusting UAV-BS antenna array element [26] spacing, increasing the number of antennas, flexible mobility, and efficient mechanical beam-steering, network performance can be improved.

Caching at the base station is one of the approaches to reduce the transmission delay and to improve throughput [27]. Since the users are normally moving around, it is not efficient to perform caching in all base stations as it increases memory requirements and loading to the BS. UAV-BS can be a solution for this kind of scenario. UAV-BS can track the user and provide the required data. If UAV-BS knows the user mobility pattern, it can optimally adjust the position and provide the desired services to the users.

2.4.4 UAV Challenges

Air-to-Ground Channel Modelling

In wireless communication, the medium between the transmitter and receiver affects the signal propagation. In this regard, air-to-ground (A2G) channel model characteristics are important for UAV-BS communications. There is a requirement to model the A2G channel in order to plan the optimal deployment. Generally, ray-tracing techniques are in practice. The A2G channel model mainly depends on the altitude of the UAV, elevation angle and propagation environment [5].

In [28], air-to-ground channels and models are presented with A2G channel models for L and C bands, and measurement-based modelling for UAV communications. Authors in [29] have provided a comprehensive survey for large-scale and small-scale fading models. In [30], the authors have studied about path loss modelling for high altitude A2G channels. In [31], the authors have studied about the elevation-dependent shadowing model for HAPs, considering LoS and NLoS paths between HAP-UAVs and associated ground users. In [32], the authors derived the likelihood of LoS path for the A2G channel based on elevation angle and the average height of the buildings.

Trajectory Optimization

In smart cities, caching related applications need proper trajectory planning for the UAV-BS to enhance performance and spectral efficiency. The trajectory is affected by several factors, such as the demand of the ground users, energy constraints, flight time and collision avoidance algorithm [5]. Trajectory optimization needs mobility and various QoS related metrics. Solving those problems is analytically more challenging.

The study about joint trajectory and communication design [33] provided the algorithm for jointly optimizing user scheduling and maximizing the minimum rate for ground users. In [34], the authors developed an algorithm to find an optimal trajectory for maximizing sum-rate in uplink communication. In addition, the study [35] investigated the optimal path planning while considering collision avoidance, no-fly zones, and altitude constraints. The authors used mixed-integer linear programming to minimize fuel consumption while finding the optimal trajectory.

Performance Analysis

A detailed evaluation of the design parameters is important to verify the system performance. In this regard, UAV-BSs in wireless communication needs a comprehensive analysis based on QoS related KPIs such as throughput, availability, coverage performance, and energy consumption [5]. There is a challenge in analysing the performance in UAV-BSs than in conventional BSs. The terrestrial BSs are not moving and they have a sufficient amount of energy to run continuously. In contrast, UAV-BSs are not static and they have stringent energy limitations. Therefore, there is a concern to define a new approach to do performance evaluation.

In [36], the authors evaluated the performance based on the transmission rate and end-to-end delay. In their study about micro unmanned airborne communication relays for cellular networks, the authors have discussed the throughput of the cellular network [37]. In [38], the authors have investigated about optimization of mobile ad hoc networks (MANETs) evaluating the probability of successfully connected devices. In the study [39] about the wireless relay communication with UAVs, the authors derived the closed-form equation for signal-to-noise-ratio (SNR) changes and evaluated the ergodic capacity of the UAV-ground links. In addition, the authors derived the expression for downlink coverage for ground users in the multi-UAV network in [40].

Optimal Deployment

3D placement of UAV-BSs in a heterogeneous network is addressed as a challenging problem [5, 41, 42]. In [41], which concentrates on the 3D placement of drone BSs in wireless cellular networks, the authors have proposed a heuristic algorithm-based approach to position the UAV-BSs in various geographical areas with different user densities. The goal of that research was to find the minimum number of drones and their 3D positions. In [42], the authors proposed drone positioning for user coverage maximization, where two techniques are proposed. First approach is the successive deployment of aerial BSs and the other approach is the simultaneous deployment of multiple aerial BSs with k-mean clustering. According to [43], ray-tracing simulations incorporated with ITU channel models are investigated. In this environment-aware investigation, authors have discussed different channel models which mostly affect the placement of UAV-BSs in real-world scenarios. In addition, in [44], the authors investigated about UAV positioning based on three different approaches. The first approach is positioning the UAV is done such that the number of ground users connected by the UAV is maximized. Second approach is to analyse the minimum number of UAV-BSs to provide the full coverage to the ground users in a particular geographical area. Minimizing the total flight time while maintaining the ground user loads are discussed with the Google earth simulator is the third approach which they have investigated.

The study of multiple drone cell deployment and optimization in [45] proposed UAV based radio access network with relays. There, user coverage and drone-to-base-station (D2B) communication features are analyzed. The optimization part discussed maximizing the user coverage while keeping the D2B quality. Particle swarm optimization (PSO) algorithm is used for the solution approach. In another evolution-based approach presented in [46], authors have studied about joint positioning of UAV-BS and user association proposed the method for maximizing user satisfaction by providing required data rates. There the authors investigated the best possible UAV-BS positioning. In addition to that, they have proposed two different ways for user association: genetic algorithm (GA) and particle swarm optimization (PSO). UAV based dynamic coverage in heterogeneous networks is investigated in [47], where authors have proposed UAV based floating relay (FR) cell deployment inside the existing macrocell in order to achieve dynamic and adaptive coverage. Another multiple drone-based positioning is discussed in [48]. There, the authors proposed exact potential game theory (EPG) and Nash equilibrium (NE) points based positioning in order to perform coverage maximization and power control.

Previous research on improving performances of UAV-BSs by dynamic repositioning of the base stations [49] proposed an algorithm to automatically control and reposition BSs according to the user activities and movements. They have compared the spectral efficiency between the fixed positioning of drones and dynamic repositioning. In this study, single drone, single-user based dynamic reposition is analyzed, then optimizing the spectral efficiency and minimizing the interference by dynamic prepositions are evaluated in multi-cell environments are discussed. Another research about positioning UAV relays for vehicular communication in full-duplex scenarios proposed an algorithm to find the positions of the UAV relays in order to satisfy the QoS requirements [50]. The authors in [51] studied location optimization for the multiple access channel between UAVs and vehicles in visible light communication. Based on their simulation results, they have shown that the position of the UAV influences the capacity of the vehicles.

Numerous studies which have been done in the area of UAV positioning clearly indicate that the role of the UAV position is very important for different kinds of applications. In [52], authors have studied about the positioning of drones in order to maximize the throughput in the software-defined network for disaster areas. The proposed algorithm works with the data collected and stored in the system via a software-defined network. According to the data, the most suitable positions for different flows are determined. Another study on UAV trajectory planning with jamming is investigated in [53]. They have proposed a convex optimization based solution for different speeds of the UAV. Besides, they have discussed static deployment scenarios as well.

3 POSITIONING OF MULTIPLE UAV-BASE STATIONS

3.1 System Model

Consider a multi-UAV aided mmWave wireless communication system as shown in Figure 3.1, which consists of D UAVs. The set of base stations equipped with N number of antennas. All UAV-BSs are represented by the set $\mathcal{D} = \left\{1, 2, \ldots, D\right\}$. The location of jth UAV-BS is given by (x_j, y_j, z_j). We denote the set of all single antenna users associated with jth UAV-BS by $\mathcal{U}_j = \left\{1, 2, \ldots, I_j\right\}$. We assume that all the users are located inside a predefined square region, which is bounded by the coordinates (x^j_{min}, y^j_{min}) and (x^j_{max}, y^j_{max}) on xy-plane for every UAV-BS. The location of a user $k \in \mathcal{U}_j$ is given by (x^j_k, y^j_k, z^j_k). Each user is associated with a single UAV-BS. We assume that there is no impact on UAV-BS downlink transmission due to orientation drifts. All users assigned in a fixed location and UAV-BS can move any direction in x,y,z planes to provide services to users.

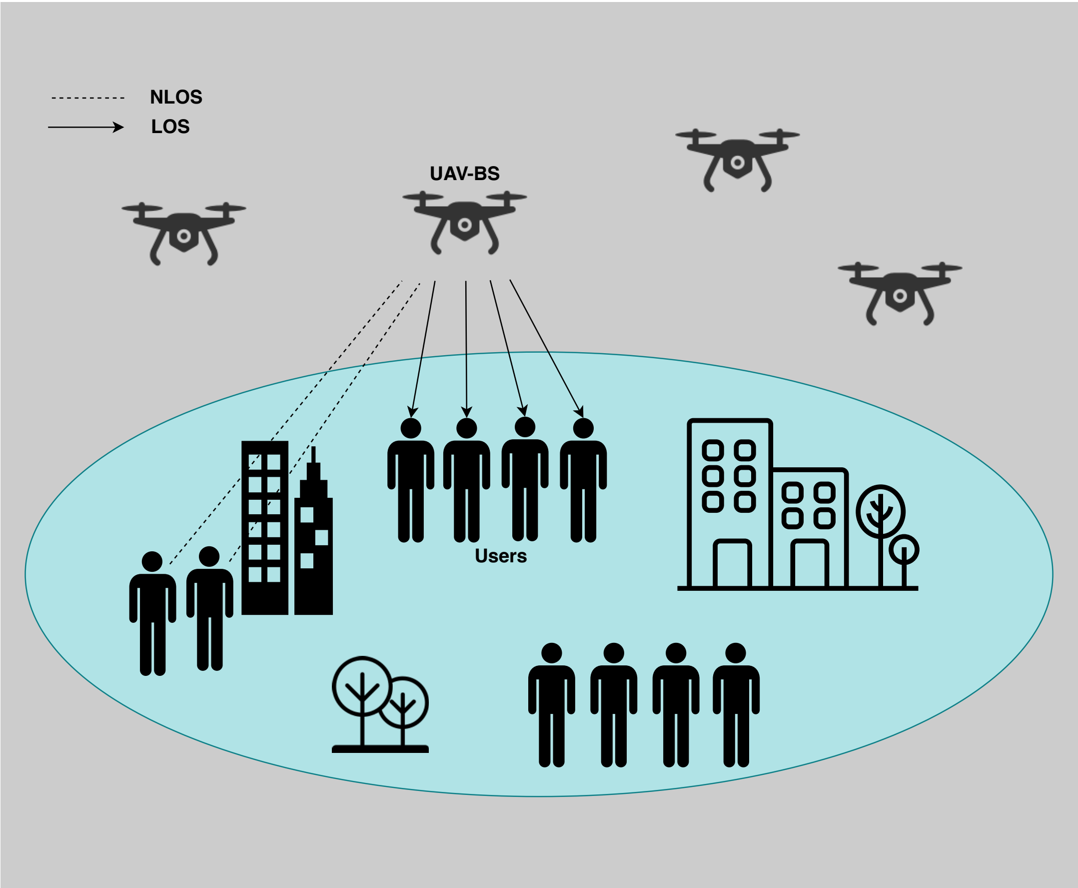

Figure 3.1. System Model

In this study, we consider all users are uniformly distributed. Furthermore, MISO downlink wireless communication only considered in this thesis.

3.1.1 Air to Ground Channel Model

The air to ground channel between jth UAV-BS and kth user of the UAV-BS j is given by

$$\mathbf{h}_{j,k}^{j} = \sqrt{N} \sum_{p=1}^{N_P} \frac{\alpha_{k,p} \ \mathrm{a}(\theta_{k,p})}{\sqrt{1 + (d_k^j)^{\gamma}}}, \tag{1}$$

where N_p is number of multi-paths, $\alpha_{k,p}$ is the gain of p-th path, $\alpha_{k,p} \in \mathcal{CN}(0, 1)$. The notation $\theta_{k,p}$ is angle-of-departure(AoD) of the p-th path, γ is the path loss exponent. The notation d_k^j is the distance between the serving UAV-BS $j \in \mathcal{D}$ and the user $k \in \mathcal{U}_j$ is given by

$$d_k^j = \sqrt{(x_k^j - x_j)^2 + (y_k^j - y_j)^2 + (z_k^j - z_j)^2}. \tag{2}$$

The directive vector $\mathrm{a}(\theta_{k,p})$ associated with AoD $\theta_{k,p}$ is defined as

$$\mathrm{a}(\theta_{k,p}) = \frac{1}{\sqrt{N}} \left[1 \ e^{-j2\pi \frac{M}{\zeta} \sin(\theta_{k,p})} \ldots \ e^{-j2\pi \frac{M}{\zeta} \sin(\theta_{k,p})(N-1)} \right]^T, \tag{3}$$

where M is the antenna spacing, and ζ is the wavelength of the carrier frequency. As presented in [54, 55], mmWave channels have the Non-Line-of-Sight (NLoS) paths which are normally 20 dB weaker than LoS paths. In this study, we assume that all the users have LoS paths, because UAV-BS is hovering at high altitudes and a very small amount of scatters around UAV-BS in the air interface [54]. Therefore, as discussed in [56, 57], we consider only the LoS path for further study in mmWave channels. Hence, equation (1) becomes

$$\mathbf{h}_{j,k}^{j} = \sqrt{N} \frac{\alpha_k \ \mathrm{a}(\theta_k)}{\sqrt{1 + d_{j,k}^{\gamma}}}, \tag{4}$$

where α_k is the complex gain and θ_k is the AoD of the LoS path.

3.2 Problem Formulation

The received signal of the kth user of jth UAV-BS $\mathbf{r}_{j,k}$ is defined as

$$\mathbf{r}_{j,k} = \sqrt{p_{j,k}} (\mathbf{h}_{j,k}^{j})^{\mathrm{H}} \mathbf{w}_{j,k} s_{j,k} + \sum_{\substack{i \in \mathcal{U}_j \\ i \neq k}} \sqrt{p_{j,i}} (\mathbf{h}_{j,k}^{j})^{\mathrm{H}} \mathbf{w}_{j,i} s_{j,i} + \sum_{\substack{l \in \mathcal{D} \\ l \neq j}} \sum_{i \in \mathcal{U}_l} \sqrt{p_{l,i}} (\mathbf{h}_{j,k}^{l})^{\mathrm{H}} \mathbf{w}_{l,i} s_{l,i} + n_k \tag{5}$$

where $p_{j,k}$ is the transmit powers from jth UAV-BS to kth user, $\mathbf{h}_{j,k}^{l}$ is channel vector between kth user and lth UAV-BS, $\mathbf{w}_{j,k}$ is spatial directivity of the signal sent to user k from jth UAV-BS, and $s_{j,k}$ is scalar data symbol sent from jth UAV-BS to kth user. In equation (5), the first part is the desired signal that the user k receives from UAV-BS j. The second part is interference from the UAV-BS j to user k while transmitting to other users. The third part is multi-user interference from other UAV-BSs to user k $\in \mathcal{U}_j$. The fourth part is additive white Gaussian noise $n_k \sim \mathcal{CN}(0, IN_0)$. The downlink signal-to-interference-plus-noise ratio (SINR) of the kth user is given by

$$\Gamma_{j,k} = \frac{p_{j,k} |(\mathbf{h}_{j,k}^{j})^{\mathrm{H}} \mathbf{w}_{j,k}|^2}{N_0 + \sum_{\substack{i \in \mathcal{U}_j \\ i \neq k}} p_{j,i} |(\mathbf{h}_{j,k}^{j})^{\mathrm{H}} \mathbf{w}_{j,i}|^2 + \sum_{\substack{l \in \mathcal{D} \\ l \neq j}} \sum_{i \in \mathcal{U}_l} P_{l,i} |(\mathbf{h}_{j,k}^{l})^{\mathrm{H}} \mathbf{w}_{l,i}|^2}. \tag{6}$$

Figure 3.2 illustrate the geographical area. There are four predefined regions with R length. Assume every square region contains a known number of users.

Our goal is to position the UAV-BSs one per each square in an optimum location. Let $l_i \in \mathbb{R}^3$ be i-th location a UAV-BS can operate in a predefined square region. We assumed that all the users inside every square are associated with respective UAV-BS only. Elements of l_i are x, y, and z coordinate points, respectively. Hence the location matrix can be expressed as

$$L_D = \begin{bmatrix} x_{d1} & y_{d1} & z_{d1} \\ x_{d2} & y_{d2} & z_{d2} \\ \vdots & \vdots & \vdots \\ x_{dl} & y_{dl} & z_{dl} \end{bmatrix}. \tag{7}$$

Similarly, every UAV-BS in this network has a predefined set of locations in their respective square region that if operates. Therefore there are many combinations of predefined locations for all UAV-BS. The total number of combinations can be expressed as

$$c = {N_{pd}}^D, \tag{8}$$

where N_{pd} is number of predefined locations inside each square, and D represent the number of UAV-BS, in the network. According to the regulatory guidelines mentioned in Table 1, there are limiting factors for the deployment of UAV-BS such as type, weight, speed, and trajectory. In this regard, we consider trajectory related constraints.

Figure 3.2 shows the feasible and restricted regions. UAV-BS are not allowed to operate in the restricted area but need to satisfy the coverage requirements of the users inside the area. We define elliptical restricted region. Therefore, for all $l_i \in \mathbb{R}^3$, we have:

$$(x - x_{di})^2/b^2 + (y - y_{di})^2/a^2 \geq 1 \tag{9}$$

where (x_{di}, y_{di}) are the horizontal coordinates of the UAV-BS, a is the major axis of the restricted area and b is the minor axis of the restricted area.

Second, we consider UAV-BS hovering-height related constraint. For the safety of the UAV-BS and regulations, every UAV-BS is assumed to have a minimum flying height of h_{min}. Further, UAV-BS has a maximum allowable flying height of h_{max}. Hence, for all j $\in \mathcal{D}$, we have:

$$h_{min} \leq z_{di} \leq h_{max}. \tag{10}$$

The matrix $\mathbf{S}$ is the SINR values of all the users in all possible combinations, and $\mathbf{L}$ is the all possible combinations of UAV-BS locations. We define a vector $\mathbf{e}$, which contain one entry equal to 1 and other all be null. The index of the non zero entry gives the optimum combination of locations for all the UAV-BS $j \in \mathcal{D}$. The vector $\mathbf{e}$ can expressed as,

$$\mathbf{e}^T = \begin{bmatrix} 0 & 0 & 0 & \dots & 1 & \dots & 0 \end{bmatrix}. \tag{11}$$

With consideration of vector $\mathbf{e}$, now rewrite the SINR matrix as,

$$\Gamma = \mathbf{e}^T \mathbf{S} \tag{12}$$

where, Γ is a vector of all user SINR values for a possible combination. Similarly, we rewrite the possible location matrix with consideration of vector $\mathbf{e}$ as,

$$\tau = \mathbf{e}^T \mathbf{L} \tag{13}$$

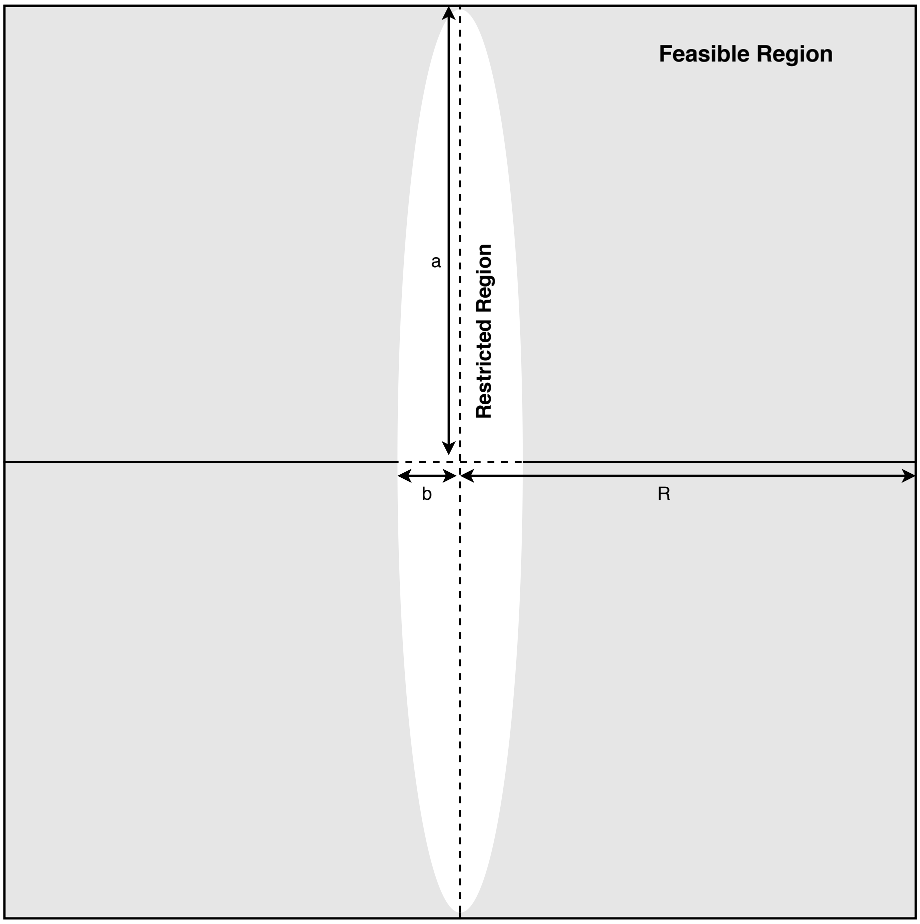

Figure 3.2. Feasible region & restricted region.

where, τ is vector of all UAV-BS positions for a possible combination. By using above constraints the problem can be formulated as the following feasibility problem

$$\begin{aligned}
&\text{minimize} \quad 0 && \text{(14a)}\\
&\text{subject to} \quad \Gamma_{j,k} \geq \Gamma_{th}, \forall k \in \mathcal{U}_j, && \text{(14b)}\\
&\quad (x - x_{di})^2/b^2 + (y - y_{di})^2/a^2 \geq 1, \forall j \in \mathcal{D}, && \text{(14c)}\\
&\quad h_{min} \leq z_{di} \leq h_{max}, \forall j \in \mathcal{D}, && \text{(14d)}\\
&\quad \parallel \mathbf{e} \parallel_0 = 1, && \text{(14e)}\\
&\quad e_a \in \Big\{0, 1\Big\},\ a = 1, \ldots, c && \text{(14f)}
\end{aligned}$$

where the variable is **e**. The problem (14) is combinatorial and NP-hard. Hence, it requires exponential complexity to get the global optimum solution. Therefore, we have to rely on sub-optimal algorithm to find the approximate solution to the problem.

3.2.1 Solution Approach

We approximate the ℓ_0 minimization problem (14) as non-combinatorial ℓ_1-norm problem. Therefore, we replaced all ℓ_0 functions as ℓ_1-norm functions. The approximated problem as follows,

$$\begin{aligned} \text{minimize} \quad & 0 && \text{(15a)} \\ \text{subject to} \quad & \Gamma_{j,k} \geq \Gamma_{th}, \forall k \in \mathcal{U}_j, && \text{(15b)} \\ & (x - x_{di})^2/b^2 + (y - y_{di})^2/a^2 \geq 1, \forall j \in \mathcal{D}, && \text{(15c)} \\ & h_{min} \leq z_{di} \leq h_{max}, \forall j \in \mathcal{D}, && \text{(15d)} \\ & \parallel \mathbf{e} \parallel_1 \leq 1, && \text{(15e)} \\ & 0 \leq \mathbf{e}_a \leq 1, \ a = 1, \ldots, c && \text{(15f)} \end{aligned}$$

where the variable is $\mathbf{e}$. Binary constraints in the problem (14e) is relaxed by (15e). However, the restricted region related constraint in this problem is non-convex which makes problem (15) unsolvable. Therefore, we approximate the restricted area to be rectangular as mentioned in Figure 3.3.

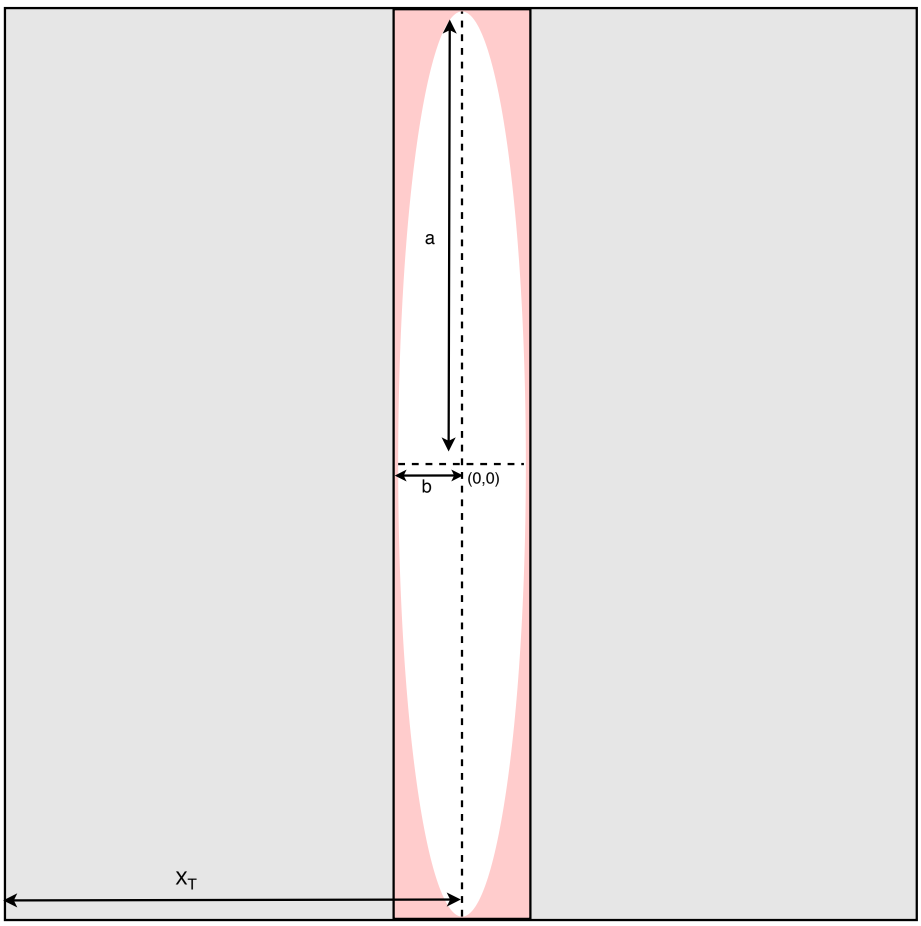

Figure 3.3. Approximated feasible region & restricted region.

We noticed that the non-convex elliptical region in the network can be approximated into linear constraints which are convex. Therefore, the problem (15) can be expressed as,

$$\begin{aligned}
\text{minimize} \quad & 0 && \text{(16a)}\\
\text{subject to} \quad & \Gamma_{j,k} \geq \Gamma_{th}, \forall k \in \mathcal{U}_j, && \text{(16b)}\\
& x_{di} \geq X_T - b, \forall j \in \mathcal{D}, && \text{(16c)}\\
& x_{di} \leq -X_T + b, \forall j \in \mathcal{D}, && \text{(16d)}\\
& h_{min} \leq z_{di} \leq h_{max}, \forall j \in \mathcal{D}, && \text{(16e)}\\
& \parallel \mathbf{e} \parallel_1 \leq 1, && \text{(16f)}\\
& 0 \leq \mathbf{e}_a \leq 1, \;\; a = 1, \dots, c && \text{(16g)}
\end{aligned}$$

where the optimization variable is $\mathbf{e}$. Therefore, this convex optimization problem can be solved by standard CVX solver. The proposed algorithm to find a feasible position for a multi-UAV aided network is summarized in Algorithm 1.

Algorithm 1 Multi-UAV-BS Positioning

1: For a given geographical area: Define cells with respect to the number of UAV-BS
2: Set predefined locations inside each cell
3: Create combination matrix for all predefined locations in the network
4: Approximate the restricted region
5: Set SINR threshold
6: Set h_{max} and h_{min} values
7: Set major axis and minor axis values of the restricted region
8: Find SINR values for all predefined combinations
9: Find the location matrix for each UAV-BS from the combination
10: Approximate the problem (15) by (16)
11: Solve (16) and $\mathbf{e}$
12: Find the index of the maximum value in $\mathbf{e}$, and locate the UAV-BSs

4 SIMULATION RESULTS AND DISCUSSION

We consider two different scenarios for the deployment. First one is the positioning of a single UAV-BS in a single cell with a set of associated users. In this case, we consider a square 20 m x 20 m area with 200 predefined locations for the UAV-BS to deploy in 3D-space. Second one is the positioning of the multiple UAV-BSs considered. We consider 114 m x 114 m geographical area, which consists of 4 cells each with 12 predefined locations. The users in both cases have fixed locations. They are randomly generated. We assume UAV-BS's orientation and stability are well controlled. Therefore, there are no orientation drifts on UAV-BS's downlink transmission.

4.1 The Positioning of a Single UAV-BS

For our simulation, we consider a single cell with two single antenna users. Users are assumed to be at ground level, (z = 0). We allocate equal power to all the users with beamforming. Table 4.1 presents the simulation parameters for the UAV-BS deployment.

Table 4.1. Simulation parameters for positioning a single UAV-BS

Description	**Value**
Size of the cell	20 m x 20 m
Number of Users	2
Number of UAV	1
Number of antennas in a UAV-BS, N	6
Path-loss exponent, γ	2
Restricted region, b	4 m
UAV-BS transmit power	1 mW
Noise, N_0	-35 dBm
h_{min}	5 m
h_{max}	20 m

Figure 4.1 illustrates the SINR versus user index at one of the feasible location. It can be observed that the users achieved the SINR target value of 3 dB for the ℓ_1-norm minimization problem.

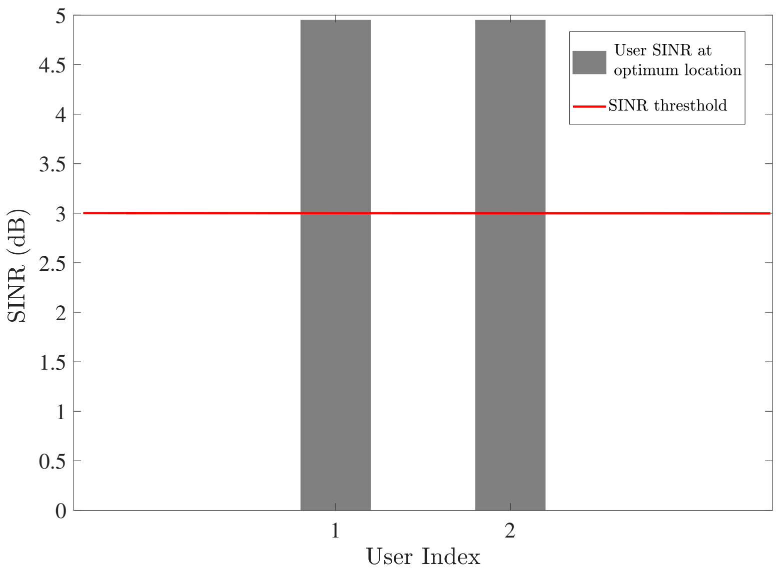

Figure 4.1. SINR versus user index at a feasible location.

Figure 4.2 shows the user distribution and a feasible position for the UAV-BS. This figure confirms the proposed algorithm chooses feasible positions only outside the restricted region. The proposed algorithm satisfies the operating region of constraint.

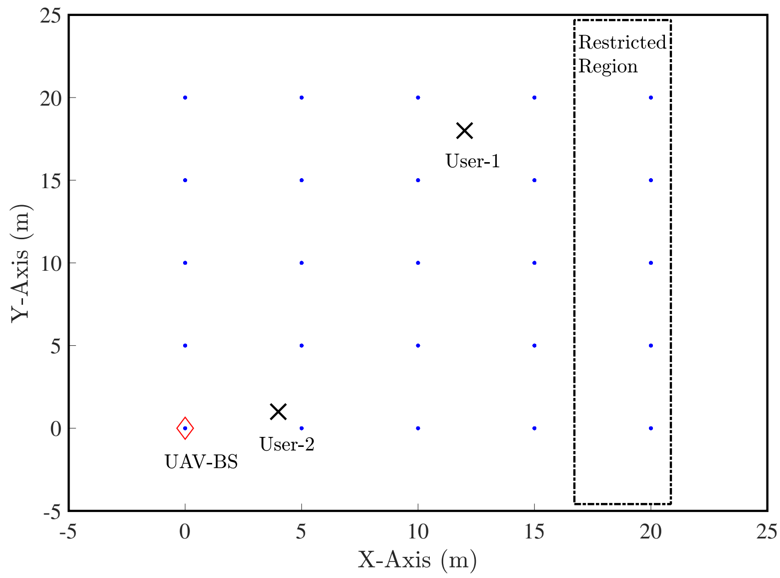

Figure 4.2. User locations and the feasible position of the UAV-BS.

We simulate 30 different SINR target values for the same user distribution, and plot Figure 4.3. We keep other constraints same during the simulation. We can observe the feasible positions are spread outside the restricted region. Also, we notice some feasible positions for different SINR values are same in xy-plane and different in z-plane. Therefore we were able to plot only a few points in Figure 4.3.

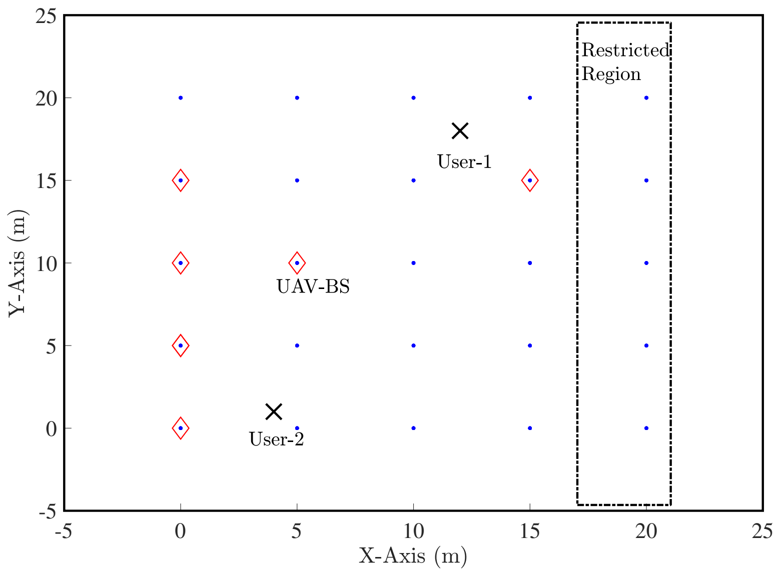

Figure 4.3. User locations and the feasible positions of the UAV-BS for different SINR target values and same user distribution.

We simulate 30 different user distributions for the same SINR target value, and plot Figure 4.4. We kept the height and the restricted region constraints same during the simulation. We observe the algorithm finds the feasible locations outside the restricted region.

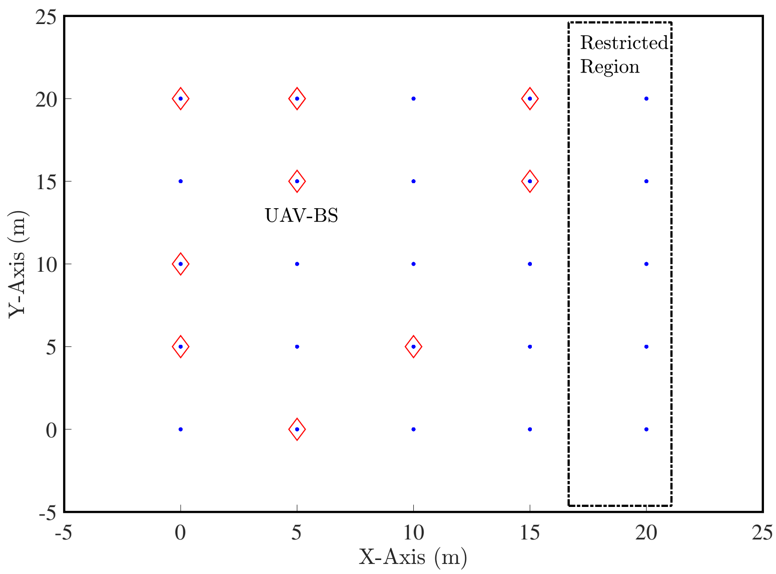

Figure 4.4. Feasible positions of the UAV-BS for same SINR target value and different user distributions.

Figure 4.5 illustrates the 3-D positions of the UAV-BS for different user distributions. This figure confirms the proposed algorithm satisfies the height constraint. Figure 4.6

presents the xz-plane of the Figure 4.5. It can be observed that there is no UAV-BS placed inside the restricted region.

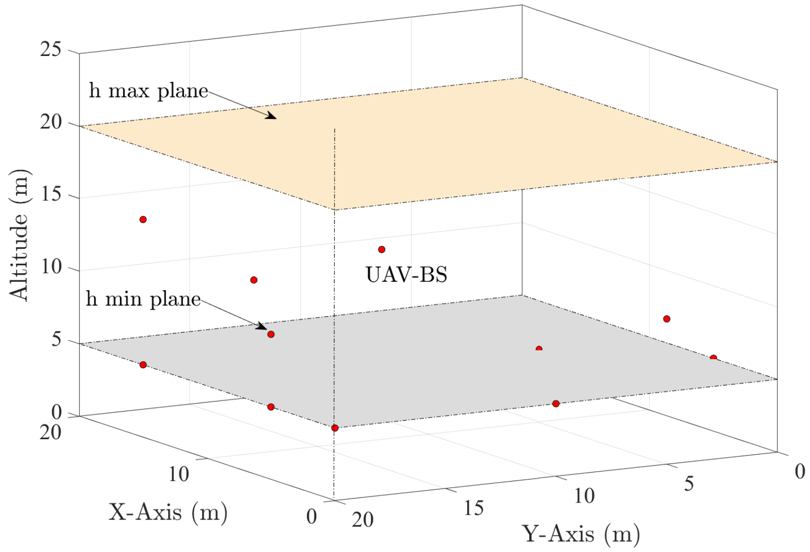

Figure 4.5. Positions of the UAV-BS for different user distributions in 3-D space view.

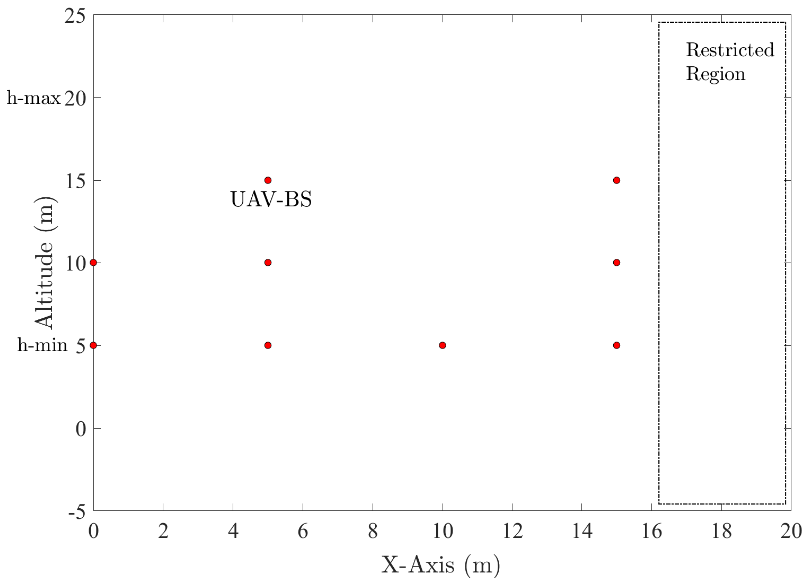

Figure 4.6. Positions of the UAV-BS for different user distributions in xz-plane view.

4.2 The Positioning of Multiple UAV-BSs

We consider 4 UAV-BSs to provide services to 20 single-antenna users inside a defined geographical area. The given area is equally divided into 4 square regions. Every region contain a UAV-BS and 5 associated users. Each user can be served by only one UAV-BS. Users are assumed to be at ground level, (z = 0). We allocate equal power to all the users with beamforming. We predefined 12 locations for the deployment in each region. Hence, there are 20,736 combinations defined for the simulation. Our goal is to find the feasible set of locations out of 20,736 combinations. Table 4.2 presents the simulation parameters for multi-UAV-BS deployment.

Table 4.2. Simulation parameters for positioning multi-UAV-BSs

Description	**Value**
Size of the total area	114 m x 114 m
Size of one region	57 m x 57 m
Number of User per region	5
Number of defined areas	4
Number of UAV-BSs	4
Number of UAV-BS antenna, N	6
Path-loss exponent, γ	2
Restricted region, b	9 m
h_{min}	22 m
h_{max}	32 m
UAV-BS transmit power	1 mW
Noise, N_0	-35 dBm

Figure 4.7 shows SINR versus user index at one of the feasible location for multi-UAV-BS scenario. It can be observed that the users achieved the SINR target value for the ℓ_1-norm minimization problem. Consider the region one and two, where the users are indexed by 1 to 5 and 6 to 10. It can be observed the SINR value at the feasible position and SINR value at the highest altitude are same. Therefore, the proposed algorithm chooses the highest altitude to place the first and second UAV-BSs. In the third region, both SINR values are at highest (30 m) and lowest (20 m) altitudes are less than the in between height. Therefore, the algorithm chooses the position at 25 m to deploy the UAV-BS. In the fourth region, lowest altitude (20 m) has the higher SINR value than the position selected by the algorithm (25 m). This is caused by the minimum height constrain of 22 m.

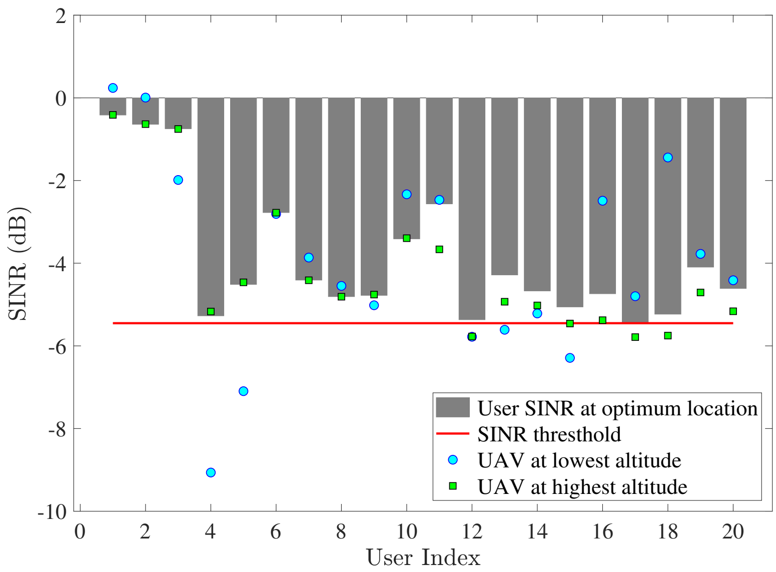

Figure 4.7. SINR versus user index at a feasible location and SINR values at highest and lowest altitudes.

Figure 4.8 presents the user distribution and a set of feasible positions for the UAV-BSs. This figure confirms the proposed algorithm chooses feasible positions only outside the restricted region. It satisfies the operating region of constraint.

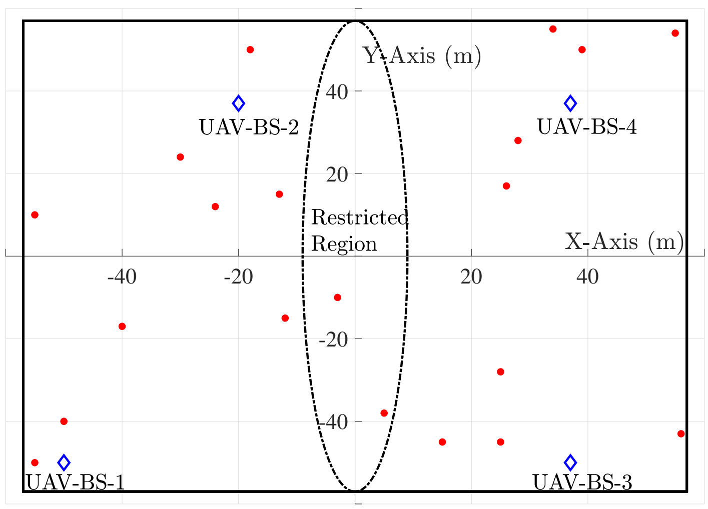

Figure 4.8. User locations and feasible positions of the UAV-BSs.

We simulate 50 different SINR target values for the same user distribution, and plot Figure 4.9. We keep other constraints same during the simulation. We can observe the feasible positions are spread outside the restricted region. Also, we notice some feasible positions for different SINR values are same in xy-plane and different in z-plane. Therefore, we able to plot only a few points in Figure 4.9.

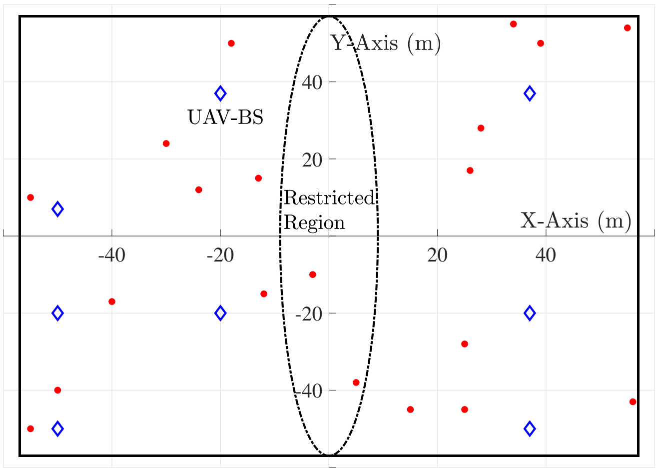

Figure 4.9. User locations and the feasible positions of the UAV-BSs for different SINR target values and same user distribution.

We simulate 50 different user distributions for the same SINR target value, and plot Figure 4.10. We observed 45 user distributions achieved the SINR threshold value. Our proposed algorithm outputs the same UAV-BS positions for some different user distributions. We kept the height and the restricted region constraints same during the simulation. It can be observed the feasible locations are spread outside the restricted region.

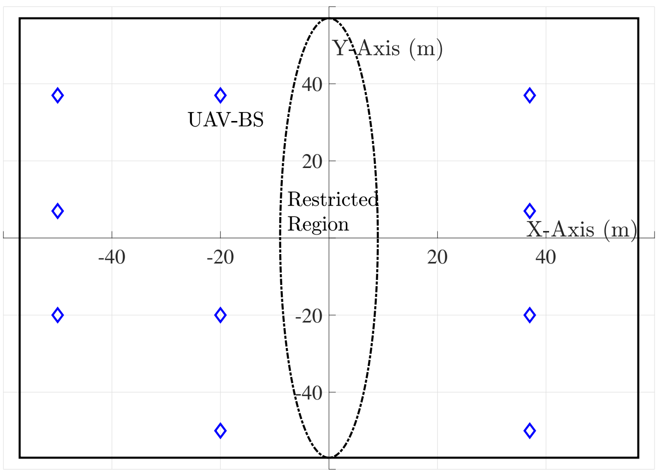

Figure 4.10. Feasible positions of the UAV-BSs for same SINR target value and different user distributions.

Figure 4.11 demonstrates the 3-D positions of the UAV-BSs for different user distributions. It can be observed all the possible locations are spared in between the h_{max} and h_{min} planes. This figure confirms the proposed algorithm satisfies the height constraint. Figure 4.12 presents the xz-plane of the Figure 4.11. It can be observed that there is no UAV-BS placed inside the restricted region.

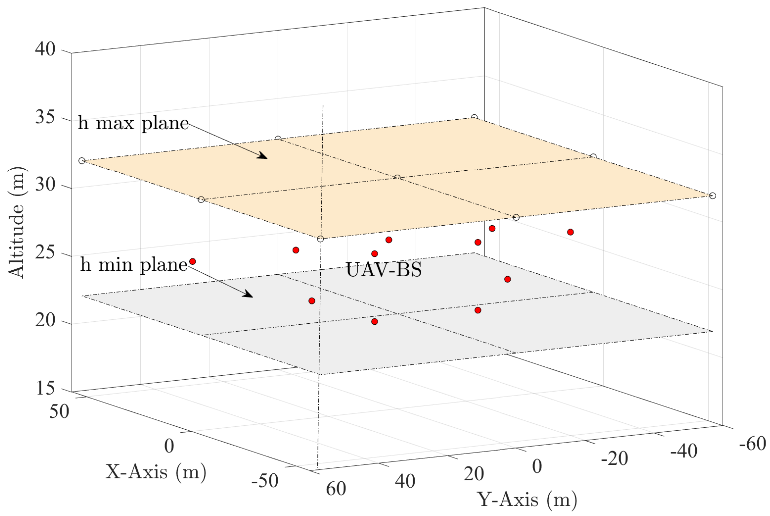

Figure 4.11. Positions of the UAV-BSs for different user distributions in 3-D space view.

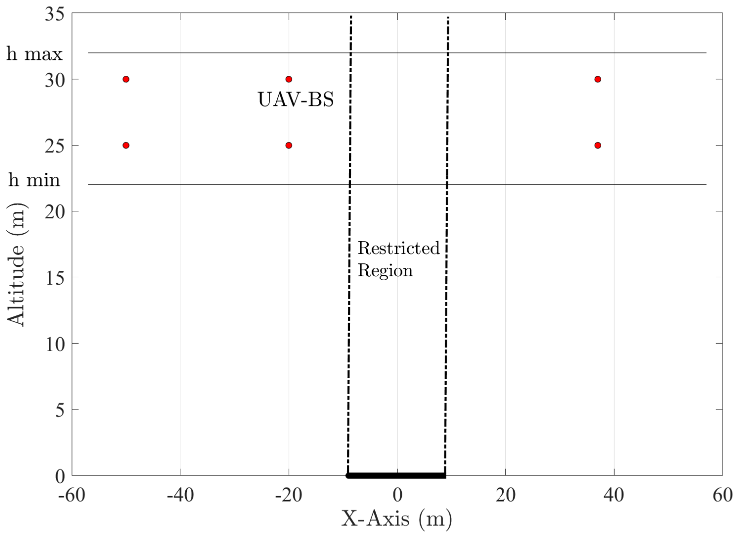

Figure 4.12. Positions of the UAV-BSs for different user distributions in xz-plane view.

5 CONCLUSION AND FUTURE WORK

In this study, three-dimensional deployment of multiple UAV-BSs in a millimeter-wave network was investigated. We developed a novel algorithm to position the UAV-BS in 3-D air space. The algorithm was tested for single region and multiple regions scenarios. The given geographical area divided into number of sub regions, which include a restricted zone to operate. First, we set predefined location for UAV-BS to operate in a sub region. Then, combinations of all possible positions are calculated. After that, we have derived the SINR values for all users in the geographical area for all the combinations. Furthermore, UAV-BS's hovering altitude was also taken into account. We have formulated a ℓ_0 norm minimization problem.

The formulated problem is a combinatorial, and NP-hard. Therefore, we approximated the elliptical restricted region into rectangular restricted region and used ℓ_1 norm approximation, which results in a solvable convex optimization problem. Finally, we numerically show the proposed algorithm satisfies the constraints and reaches to the near-optimal location for both single sub region and multiple sub regions.

Positioning of multiple unmanned aerial vehicles in millimeter-wave communication was analyzed with constraints of SINR, hovering altitude, and restricted region. We considered directional beams to serve the users inside the predefined region, further research could also be conducted to determine the effectiveness of optimal beamforming.

Massive MIMO based deployment also be consider for further research could be carried out to establish the massive MIMO based deployment. In this investigation, only one elliptical restricted region was considered. Multiple restricted regions with different shapes could be taken into account for further study.

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