Performance Analysis of mmWave drone-assisted 5G Hybrid Heterogeneous Network

By

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Approval

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Abstract

Unmanned aerial vehicles (UAVs) provide us with the ability for rapid, on demand, and infrastructure-less deployment. This capability can be exploited to meet the rising demands of futuristic fifth generation (5G) and Internet of things (IoT) networks. In this study, we consider a downlink scenario in a multi-tier heterogeneous network (HetNet) to meet the network quality-of-service (QoS) requirements. The considered QoS metrics are network coverage and data rates. We evaluate our proposed network in two different scenarios. In the first scenario there is no terrestrial communication infrastructure, while in the second case UAVs assist the already existing communication infrastructure. We study impact of various network configurations, by varying number of UAVs in the HetNet, number of users, and bias factor for mmWave tier. Our results validate that UAVs can be deployed in a standalone role as well as coexist with terrestrial infrastructure. Through extensive simulations, we propose and implement methodology to configure the HetNet for an efficient coverage-rate trade off, while meeting desired QoS metrics at the same time.

Dedication

I dedicate this thesis to my family for their valuable support and prayers through out my life

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

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List of Abbreviations

ABS	Aerial base station
SBS	Small base station
MBS	Macro base station
HetNet	Heterogeneous network
PPP	Poisson point process
IoT	Intenet-of-things
UHF	Ultra high frequency
UAV	Unmanned aerial vehicle
SNR	Signal-to-noise
SINR	Signal-to-interference and noise
mmWave	millimeter-wave
HAP	High altitude platform
LAP	Low altitude platform
UDN	Ultra dense network

M2M	machine-to-machine

Chapter 1

Introduction and Background to Thesis

1.1 5G Heterogeneous Networks (HetNets)

To keep up with increasing diversity of communication networks, 5G and beyond network architectures need to become more heterogeneous, diverse and flexible. According to cisco visual networking index (VNI 2017-2022) [1] 5G networks have evolved from field trials and limited deployment into a capable and robust network technology. As the demands for networks increases, academia and researchers believe that deployment of 5G on a full scale is the only means to fulfill the ever increasing demands of users and networks. The requirements that future networks are required to meet are broadly classified as [2]

- Capacity Enhancement: 5G networks are expected to enhance the capacity of existing mobile networks considerably in terms of coverage and data rates. Data rates of 1Gbps and above are expected from 5G networks.

- Massive Connectivity: With the emergence of concepts such as smart cities, smart parking, smart cars the need for massive connectivity among devices has increased manifolds. Massive connectivity in form of machine-to-machine (M2M) [3–6] or Internet-of-things (IOT) sensors is required for sustenance of future networks
- Low Latency Applications: The futuristic concepts of critical applications such as self driving cars, e-health services, and industrial applications of communications have made low latency and ultra-reliable communication services indispensable for 5G networks.
- Dynamic Resource Allocation: 5G networks will need to cater for demands of wide variety of users ranging from low bandwidth applications like smart grids [7] to bandwidth hungry applications like augmented reality and streaming of HD videos. 5G networks must allocate resources in a dynamic and consistent matter [8–11] to fulfill requirements of the users and networks.
- Wide Spectrum of Applications: Future networks need to support a wide range of network applications which includes IoT sensors, surveillance cameras, self-driving cars, smart cities services and a range of industrial applications.

1.2 Why mmWave HetNets?

The seemingly endless network applications have created a spectrum scarcity which has forced academia and researchers to further explore the radio wave spectrum to resolve the spectrum crunch issue. millimeter-wave (mmWave) spectrum enables us to utilize massive chunks of unexplored bandwidths that can fulfill data rate requirements of bandwidth hungry applications [12–15]. Utilization of mmWave seems the best solution to resolve the global shortage in bandwidth. However, mmWave spectrum has very different transmission characteristics as compared to ultra high frequency (UHF) spectrum. Therefore, efficient deployment of mmWave base stations is required to cater for the higher mmWave path loss. Authors in [16] have proposed a solution in which macro base stations (MBS) operating on UHF frequencies will be overlaid with small base stations (SBS) operating on mmWave frequencies. This HetNet consisting of both UHF and mmWave spectrums will form the basis of 5G networks. In [17–20] coverage and rate analysis and optimization has been done for 5G heterogeneous networks. According to [21], if we compare data rates provision capability between mmWave and UHF spectrum then as compared to mmWave base stations ten times more UHF base stations are required to provide $100Mbps$ data rates per user. Therefore, it is an unchallenged fact that to meet the huge data rate requirements of users mmWave base stations must be an essential part of any 5G networks. Coverage and rate analysis of such a network in which mmWave MBS are overlaid with mmWave SBS has been performed in [22]. Owing to the heterogeneity of 5G networks user association schemes in such networks is also an active area of research [19]. mmWave heterogeneous not only improves the coverage and rate performance of a network but through efficient resource allocation schemes can also be more energy efficient [23]. Therefore, overlaying of a network with mmWave small cells considerably enhances the capacity and energy efficiency of the HetNet.

1.3 Case for Drones Usage

According to the study in [24], future wireless networks need to cater for broad range of scenarios including provision of communication services in case of unexpected events of temporary nature like a natural disaster or a sporting event or festival. Unmanned aerial vehicle (UAV)-assisted cellular communication is a considerably new avenue which is being explored by academia and industry due to infrastructure less deployment and placement in 3D space that can help networks keep up with the ever increasing user demands and scenarios [25]. Provision of abilities such as rapid mobility and flexibility makes aerial base stations (ABSs) an important building block for next generation network architecture. ABSs can be utilized in a wide spectrum of applications ranging from emergency services in public safety network to capacity enhancement in ultra dense networks (UDNs). Over the past few years UAVs have grabbed the interest of researchers and industry who want to improve the existing systems or propose new solutions by incorporating UAVs in their models [26]- [27].

1.3.1 UAVs : Applications

UAVs, owing to their flexibility and capability of deployment in 3D space have excited researchers for a considerable time. The capabilities of UAVs were initially found suitable for surveillance purpose where aerial devices were deployed to sneak in behind enemy lines without endangering human lives. UAVs rapidly evolved and found its applications in multitude of scenarios including search and rescue operations and monitoring of a particular region. Deployment of UAVs for agriculture, surveillance, mapping and aerial sensor network has been proposed. Authors in [28] believe that UAVs will find its utilization in plethora of civil and commercial applications including search and rescue operations, real time traffic monitoring and range of other smart applications which can capture market of upto $\$45 Billion$.

1.3.2 UAVs : Classification

UAVs, depending on their heights, can be broadly classified into two categories [29],

- low altitude platforms (LAPs): These platforms can fly at an altitude of few meters upto a few kilometers. LAPs can be highly mobile, flexible and rapidly employable. LAPs are appropriate for applications requiring quick deployment like disaster recovery networks. However, LAPs have low endurance and needs to be replaced or recharged after some time.
- high altitude platforms (HAPs): These platforms are quasi-stationary and fly at altitudes above 17km. HAPs have high endurance and can

stay over an area for several days without any need for replacement.

Similarly, on basis of type, UAVs can be classified into

- Fixed Wing UAVs: These platforms are heavier in weight and have higher speeds. Fixed wing UAVs need to keep moving in an area.
- Quadrotors: This type of UAV have light weights and can fly either at very low speeds or remain static over a particular point.

1.4 UAVs : Cellular Service Provisioning

As UAVs gained attention in a multitude of roles, deployment of UAVs for cellular service provisioning became a real possibility. The services provided in 5G networks are dependent upon seamless connectivity and communication services for users and Internet of Things (IoTs). UAV based communication is a new paradigm for 5G and beyond network architectures. Advancement in UAV technology has made aerial base stations (ABSs) into a cost effective solution for provisioning of cellular services. Google Project Loon and Facebook Aquila has turned the idea of aerial platforms providing communication services into a well-established reality. The future roles envisaged for ABSs in 5G and beyond networks are to provide on demand connectivity as standalone airborne network or to assist already existing terrestrial cellular infrastructure. UAVs can come to assistance of terrestrial networks for multiple purposes such as offloading users from ground base stations in case of a crowded event or to enhance the capacity of existing terrestrial network. Availability of huge bandwidth in millimeter-wave (mmWave) frequencies makes it a key in managing large traffic volumes in smart cities. Enhanced line of sight (LoS) capability of UAVs make it a suitable platform for mmWave communications in urban scenarios where concrete structures can degrade communication in mmWave frequencies considerably. On demand deployment of UAVs also make it suitable for dealing with varying traffic flows in communication networks, where an optimum number of UAVs can assist existing communication infrastructure to deal with massive user demands. Similarly UAVs can reach any area inside a network where there is a bottleneck due to network congestion such as a crowded hot spot, a sporting event or a traffic jam, and relieve network load. UAVs also offers 5G and beyond networks resilience to network failures in case of a disaster or any unexpected event. Network resilience is indispensable for future networks which will be dependent upon ubiquitous sensors for automation and decision making. Rapid deployment of UAVs will be the key in allowing 5G networks to continue its operations by restoring communication services in any unforeseen scenario. Apart from complete network failure in case of disaster, meeting of huge user demands will be a key concern for futuristic network architectures. Through deployment of ABSs network coverage, in terms of data rates, can be enhanced whenever and wherever required. This will play a major role in satisfying the users and IoT requirements. Our proposed case study considers a scenario inside a 5G network in which UAVs, operating in mmWave bands, assist the existing cellular infrastructure in meeting huge user demands that have arisen due to any event. We believe that on demand UAV assisted networks, provide a quick, efficient and cost effective solution for provisioning of cellular services and meeting user demands. The key challenges and opportunities for deployment of UAVs in communication service provisioning have been discussed in [30] which considers the network architecture and channel considerations as key challenges and rapid deployment and flexibility as key opportunities in a UAV based communication service. Following are the key areas according to the authors in which UAVs can take a lead over ground based cellular services

- Ubiquitous coverage. UAVs provide operators with unique capability of being at the place and time of choice whenever required. This can easily fill gaps in existing communication services in case of a blind communication spot or in case of base station overload scenarios. UAVs reaching disaster struck areas in shortest possible time is a key consideration for researchers.

- Relaying. Suppose there is a tactical scenario in which there is an obstacle in the form of a mountain between the transmitter and receiver. We can send a UAV in the area which can hover over a point where it is accessible to both the transmitter and receiver and can act as a relay.

- Information dissemination and collection. Mobile UAVs can be deployed in a situation in which we want to carry information back and forth between two points where there is no pre existing communication infrastructure. UAV will collect information from one point and then move over a particular area or point where it can offload data to the concerned users. This capability can be exploited in an IoT network where a UAV can collect data from IOT sensors in a particular area and then offload data at the control centre for further processing

In [31] authors have discussed various techniques like Non orthogonal multiple access (NOMA), coordinated multi points (CoMP), 3D beamforming and sectoring in elevation domain as key opportunities that UAV communication offers.

1.4.1 mmWave UAV Communication

mmWave communication offers huge chunk of bandwidth which can be exploited to meet the ever increasing bandwidth demands. However, despite offering huge advantage in terms of bandwidth mmWave suffers from huge path loss and propagation and blockage effects [32]. Due to higher propagation losses compared with UHF spectrum, mmWave communication has higher outage probabilities. These shortfalls can be reduced if we deploy UAVs for mmWave communications. The reason is that UAVs can gain height and hover over a particular region and mainly operate with in line of sight (LoS) range of the receiver. This improves the coverage considerably. However, accurate knowledge of air to ground (ATG) channel characteristics in such situations is necessary and is an active area of research.

1.5 Thesis Motivation

This thesis is motivated by deployment of UAVs in a mmWave 5G network to enhance the coverage and capacity of the network. User requirements of data rates are to be fulfilled in the area for which UAVs are deployed. UAVs offers ability for on demand and rapid deployment. This capability can be exploited to form an aerial network where there is no terrestrial infrastructure or to enhance the capacity of an already existing terrestrial cellular network.

1.6 Thesis Contribution

The thesis provides the following contributions:

- We propose an aerial network consisting of UAVs operating in both mmWave and UHF spectrum to provide cellular service in a region with no existing communication infrastructure.
- Coexistence of mmWave and UHF UAVs in the same network has been proposed for the first time and valuable insights into such a network have been made in this research.
- We analyze the performance of the aerial network in terms of QoS metrics of coverage and data rates. The number of users and the data rates that can be supported in such a network.
- We analyze the behaviour of the network by varying the number of mmWave UAVs to the total UAVs in the network and analyze the network performance.
- We propose an optimum number of mmWave UAVs in the network based upon the network requirements.
- The enhancement in capacity of an already existing cellular network after it is assisted by mmWave UAVs is analyzed

1.7 Thesis Organization

The thesis is organized as follows. Chapter 2 presents the literature review for our thesis so that readers can come to terms with the background as well as the state-of-the-art in the concerned area of research. In Chapter 3, we present system model for two different scenarios of our network. In first scenario there is no pre-existing communication infrastructure and cellular service is provided by UAVs only, while in the second scenario mmWave UAVs assist terrestrial cellular infrastructure to enhance capacity of the HetNet. In Chapter 4, we analyze the performance of our proposed system model in terms of quality-of-service (QoS) metrics of coverage and data rate. In Chapter 5, we discuss in detail the results after detailed performance analysis of our proposed HetNet. In the end, we discuss the conclusions and future work of our proposed study in Chapter 6.

Chapter 2

Literature Review

Existing literature on UAV communication has focused on multiple aspects ranging from role of UAVs in scenarios such as provisioning of emergency services in public safety networks, and assisting existing cellular infrastructure in serving massive crowds during sporting events [33]. However, owing to power constraints and payload restrictions, we envisage role of UAVs in the form of aerial small cells to serve users in a particular area for a limited time when the requirement arises. This role is inline with the proposed 5G network architecture.

UAV communication, being a relatively new paradigm in 5G and beyond networks, is full of opportunities, challenges and open problems. UAV altitude is a key differentiating point which separates aerial base stations from terrestrial base stations. Authors in [34] exploited this capability to derive the optimum height which maximizes the coverage within a given area. In addition, geometric line of sight (LoS) probability dependent upon the UAV height and the environment was also derived. The authors in [35] exploited mobility of UAVs to determine optimal 3-D deployment of UAVs to maximize downlink coverage by using circle packing theory. Authors in [36] give a novel method for UAV deployment depending upon cost function-based neural network which allocates UAV to area with high traffic demands. Such an arrangement not only increases coverage and enhances capacity of the network, but also balances load and offloads terrestrial base stations in ultra dense networks. In [37], downlink signal-to-interference plus noise ratio (SINR) coverage analysis of a UAV-assisted cellular network is performed by providing an analytical framework. In the system model, a heterogeneous network is deployed in which ground base stations and UAVs are distributed according to Poisson Point Processes (PPPs). Users are modeled through Poisson Cluster Process (PCP) around ground projection of UAVs. However, multiple clusters of users around fixed points is a rare phenomenon in actual network scenarios.

Although, UAVs operating at sub-6GHz have dominated most of research, recently trend is shifting towards deployment of millimeter wave (mmWave) UAVs. Deployment of mmWave UAVs for public safety communications has been proposed in [38]. The reason for above 6GHz frequencies is that a larger available spectrum of mmWave allows to meet bandwidth requirements of critical applications. The enhanced LoS capability of UAVs makes it useful for being deployed as mmWave communication platform. Increased path loss of mmWave with distance were considered as challenge for mmWave communication from UAVs however directionality of mmWave can be used to compensate for path loss [39]. In [40], authors use tools from stochastic geometry to analyze effects of directionality and heights on signal-to-interference ratio (SIR) in mmWave UAV-based communication. It was analytically derived that increase in directivity of mmWave causes considerable increase in SIR.

2.0.1 Existing State-of-the-Art

In [41] authors have deployed mmWave UAVs in an urban environment and used ns-3 simulations to analyze performance of the system. To meet capacity demands of 5G networks densification of small cells is proposed through deployment of mmWave UAVs as drone small cells in air. As the number of UAVs in the network is increased the probability of users having a LoS connection with atleast one UAV increases. UAV-assisted data collection in a wireless sensor network (WSN) is proposed in [42]. Here UAV flies over a particular region where sensors are located and collects data. The number of UAVs and the number of cells into which region is divided is optimized through simulations. In [43] the energy efficiency of a UAV-assisted HetNet is optimized based on optimum resource allocation algorithms. However, only UHF UAVs were deployed in the HetNet. NOMA has been used for mmWave drones in [44]. It is shown that spectral efficiency of the mmWave drone improves considerably with NOMA. The authors have also derived an optimum value for transmit power after which the coverage for the network does not improve any further. Optimum altitude and power for deployment of drone small cells (DSC) has been derived in [45]. After deriving results for a single drone, the authors go on and derive optimum altitude for two drones in an interference free and interference limited scenario. Authors in [46] have derived the optimum altitude and antenna beam width at which UAV will have optimum coverage subject to maximum power constraint. When the beam width is small then the power is concentrated in a small region which reduces the coverage area however, the received power increases. Similarly when beam width increases the power received decreases but the coverage area increases. Therefore an optimum value for UAV height and beam width can be found which maximizes the ground users coverage subject to maximum power. In [47] a unified network consisting of terrestrial base stations and UAVs has been utilized using tools from stochastic geometry. The coverage and capacity enhancement of such a network has been analyzed. However, whenever we will use mmWave in a HetNet there will always be a trade-off between the coverage and rates in the network. Authors in [48] have performed such an analysis in which a trade-off between coverage and rates in a mmWave HetNet is obtained. In [49],the deployment of mmWave UAVs in addition to terrestrial network has been proposed to meet the capacity demands. Moreover spectrum management techniques for such a network ahve been proposed. As mmWave is more susceptible to losses due to propagation and blockage, authors in [50] have analyzed the blockage effects when mmWave UAVs are deployed as aerial base stations in 5G networks. The concept of aerial internet has been proposed in [50] where UAV swarms carrying intelligent routers form a MANET provide internet services at an area where there is no connectivity due to any disaster or non availability of resources. The role of mobile UAVs in reducing the age-of-information in an IOT network has been proposed in [51], where a UAV will follow an optimum flight trajectory between a source and destination and ensure that critical information like status update is provided in the IoT network. In [52] a UAV-assisted device-to-device (D2D) network has been proposed where the terrestrial base station has malfunctioned and UAV is deployed to provide emergency communication services.

2.0.2 Research Gap and Opportunities

Co-existence of sub-6GHz and mmWave communication from UAVs is an area which is full of possibilities, however, to our best knowledge, limited research has been done in such hybrid HetNets. mmWave and UHF spectrum offer unique characteristics to a network. Therefore merging both these spectra in a single network consisting of UAV offers an exciting dimension to future networks. We take such a hybrid cellular model consisting of UAVs communicating with users on ground with sub-6GHz and mmWave frequencies and analyze the coverage and rate trends in such a network. We believe that Sub-6GHz and mmWave UAVs provide unique and diverse capabilities in terms of performance and such hybrid HetNets will provide exciting opportunities in improving network performance.

Chapter 3

UAVs Deployment Scenarios & Considerations

3.1 Standalone UAVs Network

We consider a scenario, shown in Fig. 3.1, in which because of some exclusive circumstances like a sporting event or a festival users have gathered in a particular region of Interest (RoI). The RoI covers an area of $500 \times 500m^2$ unless otherwise noted. No pre-existing communication infrastructure is available at the RoI. The location of users is modeled by homogeneous Poisson point process (PPP) with intensity λ_u users/m^2. We define, n, as the total number of users in the network. The ABSs are modeled using a Matern hard core type 1 process with minimum separation/safety distance, $\delta min = 30m$, between any two UAVs. Let N be the total number of UAVs in the network, where N_U and N_{mm} are the number of UAVs operating on ultra-high frequencies (UHF) and mmWave frequencies, respectively. Here, we define another

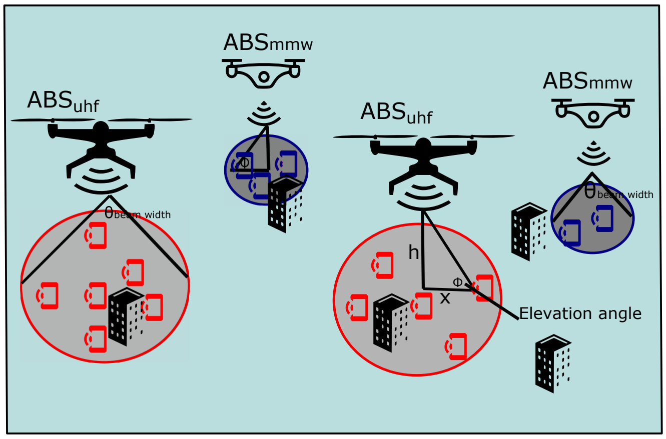

Figure 3.1: System model for HetNet

term ϵ as the number of mmWave UAVs to the total number of UAVs in the HetNet, i.e., $\epsilon = \frac{N_{mm}}{N}$.

3.1.1 Channel Model

We consider a heterogeneous network with UAVs operating at both sub-6GHz and mmWave frequencies. For LoS probability between the UAV and UE, we use geometric LoS probability model as derived in [34]. This probabilistic model for calculating LoS takes into account the elevation angle, ϕ_U, and ϕ_{mm} for sub-6GHz and mmWave UAVs, respectively. Elevation angles for both types of UAVs are calculated as

$$\phi_\zeta = arctan\left(\frac{h_\zeta}{x_\zeta}\right), \quad \zeta \in \{U, mm\}, \tag{3.1}$$

where, h_ζ denotes height of sub-6GHz and mmWave UAVs, and x_ζ is the horizontal distance of users from sub-6GHz and mmWave UAVs.

Now, we calculate the probability of LoS (PLoS), between each UAV and

UE based on model given in [34], i.e,

$$PLoS_{\zeta} = \frac{1}{1 + aexp(-b[\phi_{\zeta} - a])}, \tag{3.2}$$

where a and b are parameters depending upon environment of RoI. Similarly, the non line of sight probability (PNLoS) can be derived from LoS probability as follows

$$PNLoS_{\zeta} = 1 - PLoS_{\zeta}, \tag{3.3}$$

After we have determined the PLoS and PNLoS based on (3.1)-(3.3), we calculate the path loss for each tier based on these probabilities. For sub-6GHz UAV communication, we introduce the terms excessive path loss for LoS path, η_{LoS}, and excessive path loss for NLoS path, η_{NLoS}. We define losses for sub-6GHz UAV communication as

$$L_U = PL_U + (PLoS \times \eta_{LoS}) + (PNLoS \times \eta_{NLoS}), \tag{3.4}$$

where path loss (PL) can be calculated using the standard Friis equation

$$PL_U = 20log\left(\frac{4\pi f_{c,U} d_U}{c}\right), \tag{3.5}$$

where $f_{c,U}$ is carrier frequency of sub-6GHz UAV, d_U is the distance between the user and the sub-6GHz UAV and c is the speed of light. For mmWave UAV, we define path loss as

$$L_{mm}(d) = \begin{cases} \rho + 10\alpha_L \log(d_{mm}) + \chi_L & \text{LoS link,} \\ \rho + 10\alpha_N \log(d_{mm}) + \chi_N & \text{otherwise,} \end{cases} \tag{3.6}$$

where ρ is the fixed path loss given by $\rho = 32.4+20log(f_{c,mm})$ and χ_L and χ_N are log Normal random variables which represents the effects of shadowing in LoS and NLoS scenarios, respectively. Similarly α_L and α_N are the path loss exponents for mmwave UAV communication based on whether link is LoS or NLoS. As we have used probabilistic model for calculating geometric LoS, therefore we use weighted averaging for calculating path loss of a mmWave link based on PLoS and PNLoS from (3.2) and (3.3) as

$$L_{mm} = PLoS_{mm} \times L_{mm,L} + PNLoS_{mm} \times L_{mm,N}. \tag{3.7}$$

Now, we define equations for received power at each user whether the link is sub-6GHz or mmWave. The received power in dBs is given by

$$P_{rx,\zeta} = P_{tx,\zeta} + G(\phi_\zeta) + \mu_\zeta - L_\zeta, \tag{3.8}$$

where μ_ζ denotes multipath fading depending upon whether link established is UHF or mmWave. We take Nakagami-m fading environment where $m = 1$ for NLoS link, which is equivalent to Rayleigh fading and $m = 5$ for LoS link. Similarly $G(\phi_\zeta)$ represents the antenna gain which is a function of the elevation angle between a user and a UAV. Again we calculate multipath fading envelope value based on probabilistic values for LOS and NLoS for sub-6GHz and mmWave link as

$$\mu_\zeta = (PLoS_\zeta \times \mu_{\zeta,L}) + (PNLoS_\zeta \times \mu_{\zeta,N}). \tag{3.9}$$

We calculate the antenna gain, which is given as

$$G(\theta_\zeta) = \frac{2}{1 - cos[\theta_\zeta/2]}, \tag{3.10}$$

where θ_ζ is the elevation field of view of UHF and mmWave directionality.

3.1.2 User Association Metric

User association for the hybrid network will depend upon the maximum biased average received power, received from either sub-6GHz or mmWave UAV, given in dBs as

$$P_{rx,\zeta} = P_{tx,\zeta} - PL_\zeta + \beta_{mm}, \tag{3.11}$$

where $P_{rx,\zeta}$ is the received power, $P_{tx,\zeta}$ is the transmitted power, PL_ζ is the path loss and β_{mm} is the bias factor for the mmWave tier. Based on whatever link gives maximum value from (3.11), a user will connect to that UAV. The bias factor is an important parameter which helps us in offloading users from sub-6GHz tier to the mmWave tier based on the network and user requirements.

3.2 UAVs with Pre-existing Terrestrial Cellular Infrastructure

Our case study assumes the scenario, as illustrated in Fig. 3.2, in which a crowded hot spot is generated in particular region of interest (RoI) of a city due to traffic congestion or an exclusive event. The already existing terrestrial cellular infrastructure is insufficient to satisfy the user and services demands in the specific RoI. We assume the RoI to be spread over an area of $500m^2$. The existing cellular network in the RoI consists of a single MBS operating in the ultra high frequency (UHF) band and SBSs operating in mmWave band. The capacity of existing celular services in the area needs to be enhanced in terms of data rates. At the same time, we want to offload users from existing base stations because they are over loaded. A feasible solution to this is to deploy UAVs in the RoI till the crowd disperses and we are back to routine traffic in the RoI.

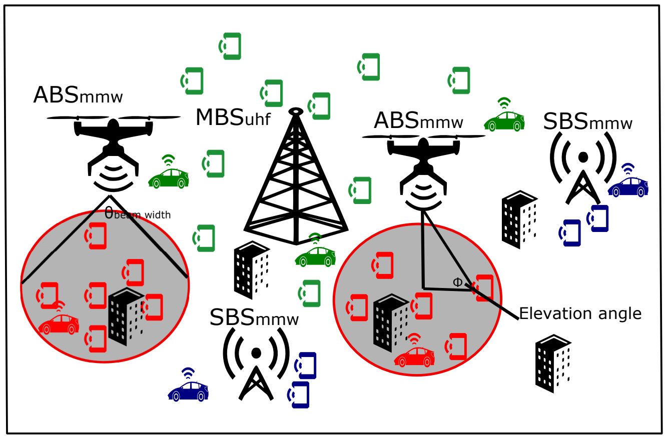

Figure 3.2: System model of HetNet with cellular infrastructure

The users in RoI are modelled through a homogeneous poisson point process (PPP) with intensity λ_u users/m^2. The MBS is assumed to be located at centre of the RoI. The SBSs are all operating in the mmWave band and are deployed at a minimum seperation distance of 100 meters from the MBS. The distribution of SBSs and UAVs is modelled according to Matern type

1 process with minimum seperation, $\delta_{SBS} = \delta_{UAV} = 40m$, between any two SBSs or UAVs. We deploy the UAVs at a minimum distances of $100m$ and $30m$ from MBS and SBSs respectively. The reason for keeping this separation is to effectively maximize the benefit of each deployed UAV in the region. If a UAV is deployed close to MBS or SBS then a user may associate with MBS or SBS instead of UAV, thereby reducing the advantage of UAV deployment in that region. We define the total SBSs in the region as N_{SBS}, and the total UAVs deployed as N_{UAV}. Similarly the total number of users in the RoI are denoted by n.

3.2.1 Channel Model

In the considered scenario, the MBS is operating in sub-6GHz frequency spectrum while the SBSs and UAVs are operating in mmWave bands. However, to minimize the interference between small cell users and UAV users, we use frequency bands of $28GHz$ and $73GHz$ for UAVs and SBSs, respectively. First we model the path loss for the UHF link, which is given, in dBs, as

$$L_U(d) = 20\log(\frac{4\pi}{\lambda_U}) + 10\alpha\log(d) + \chi_u, \tag{3.12}$$

where d is the distance between user and the connected base station, λ_U is the wavelength depending upon the carrier frequency, f_u, α denotes the path loss exponent for UHF frequencies and χ_u denotes denotes the effects of shadowing for UHF links.

Now, we define the path loss model for the SBSs operating in mmWave bands, in dBs, as

$$L_{mm}^{SBS}(d) = \begin{cases} \omega + 10\alpha_L^{SBS} \log(d_{mm}^{SBS}) + \chi_L^{SBS} & \text{LoS link,} \\ \omega + 10\alpha_N^{SBS} \log(d_{mm}^{SBS}) + \chi_N^{SBS} & \text{otherwise,} \end{cases} \tag{3.13}$$

where ω is defined as $\omega = 32.4 + 20log(f_{c,mm}^{SBS})$ and χ_L^{SBS} and χ_N^{SBS} denotes shadowing effects for LoS and non line of sight (NLoS) links respectively. While α_L^{SBS} and α_N^{SBS} are the LoS and NLoS path loss exponents depending upon whether mmWave link established between user and SBS is LoS or NLoS, respectively. For simplicity we assume that whenever the link distance d_{mm}^{SBS} is less than or equal to $30m$ the established link will be LoS and vice versa.

Now that we have clearly defined path loss models for the existing terrestrial network in the RoI, we define the path loss model for our aerial network consisting of UAVs, in dBs, as

$$L_{mm}^{UAV}(d) = \begin{cases} \gamma + 10\alpha_L^{UAV} \log(d_{mm}^{UAV}) + \chi_L^{UAV} & \text{LoS link,} \\ \gamma + 10\alpha_N^{UAV} \log(d_{mm}^{UAV}) + \chi_N^{UAV} & \text{otherwise,} \end{cases} \tag{3.14}$$

where γ is defined as $\gamma = 32.4 + 20log(f_{c,mm}^{UAV})$ and χ_L^{UAV} and χ_N^{UAV} denotes shadowing effects for LoS and non line of sight (NLoS) links respectively. While α_L^{UAV} and α_N^{UAV} are the LoS and NLoS path loss exponents depending upon whether mmWave link established between user and UAV is LoS or NLoS, respectively.

For calculating the LoS probability (PLoS) of the mmWave link established between user and UAV, the closed form expression given as

$$PLoS_{mm}^{UAV} = \frac{1}{1 + aexp(-b[\phi_{mm}^{UAV} - a])}, \tag{3.15}$$

where values of a and b depend upon statistical parameters of environment, and ϕ_{mm}^{UAV} is the elevation angle between the ground user and the UAV, given by

$$\phi_{mm}^{UAV} = arctan\left(\frac{h_{mm}^{UAV}}{x_{mm}^{UAV}}\right), \tag{3.16}$$

where h_{mm}^{UAV} is the UAV height and x_{mm}^{UAV} is the horizontal distance from the user to the projection of UAV on ground.

From (3.14) we go on to find the probability of non line of sight (PNLoS) between a ground user and a UAV as

$$PNLoS_{mm}^{UAV} = 1 - PLoS_{mm}^{UAV}, \tag{3.17}$$

Using the probabilities obtained from (3.14) and (3.16) we calculate the path loss, for a mmWave link established between a ground user and a UAV as

$$L_{mm}^{UAV} = PLoS_{mm}^{UAV} \times L_{mm,L}^{UAV} + PNLoS_{mm}^{UAV} \times L_{mm,N}^{UAV}. \tag{3.18}$$

The received power at each user from the UHF MBS is given, in dBs, as

$$P_{rx,U} = P_{tx,U} - L_U, \tag{3.19}$$

and for mmWave links the received power is given as

$$P^{v}_{rx} = P^{v}_{tx} + G(\phi^{v}_{mm}) + -L^{v}_{mm}, \quad v \in \quad \{SBS, UAV\}, \tag{3.20}$$

where for every mmWave link established, we add the directional gain of transmitting antenna to the received power equation. For UAVs we use the model in [40], given by

$$G(\theta^{UAV}_{mm}) = \frac{2}{1 - cos[\theta^{UAV}_{mm}/2]}, \tag{3.21}$$

we assume that maximum mmWave radiation is concentrated in the cone with solid angle, $\theta^{UAV}_{mm} = 30^{o}$, subtended from the UAV. Similarly directional antenna gain of SBS is calculated in same manner where ϕ^{SBS}_{mm} is the angle in horizontal plane between the ground user and the SBS and the mmWave beamwidth of the radiation pattern from the SBS is concentrated within an, $\theta^{SBS}_{mm} = 30^{o}$, arc in horizontal plane.

3.2.2 User Association Metric

Association of user with a particular tier is an important consideration in any heterogeneous network . In the considered scenario, we have a three tier HetNet with the UHF tier consisting of the MBS, while the other two tiers being the SBSs and UAVs are operating in separate mmWave bands. We associate user with any tier based on maximum biased average received power given, in dBs, by

$$P_{rx,\zeta} \; = P_{tx,\zeta} - L_{\zeta} + \beta_{mm}, \;\; \zeta \; \in \; \{U, SBS, UAV\} \tag{3.22}$$

where the power received from any tier is denoted by $P_{rx,\zeta}$, the power transmitted is given as $P_{tx,\zeta}$, the path loss associated with each tier is L_{ζ}, and the bias factor for mmWave tier, consisting of both SBSs and UAVs, is denoted by β_{mm}. Bias factor is important for mmWave tier because due to greater propagation losses power received from mmWave tier will always be lesser than UHF tier. To create a balance in the network and offload users from UHF tier to mmWave tier, based on network or user requirements, we use bias factor for mmWave tier. We can also use separate bias factor values for SBS and UAV tier, however, for our study we assume same bias factor value for mmWave tier consisting of both ground based SBSs and UAVs.

Chapter 4

Performance Analysis

4.1 Standalone UAVs Network

We assume a time division multiplex access (TDMA) scheme for each link established between a ground user and an ABS. To avoid interference, we divide the available bandwidth at each tier, sub-6GHz and mmWave, equally into the number of UAVs at that tier. For each user connected to a UAV, we calculate the signal-to-noise ratio (SNR) as follows,

$$SNR_{\zeta} = \frac{P_{rx,\zeta}}{\sigma_{\zeta}^{2}}, \tag{4.1}$$

we calculate the noise power (dB) as $\sigma_{\zeta}^{2} = -174dBm/Hz + 10log(B_{\zeta}) + NF$, where NF is the noise figure of receiver and is taken as $9dB$. For M users connected to an ABS, we calculate the downlink rate for each user as,

$$R_{\zeta} = \frac{B_{\zeta}}{M} log_{2}(1 + SNR_{\zeta}). \tag{4.2}$$

We define SNR coverage probability and rate coverage probability as two parameters for evaluating performance of the hybrid network. The SNR coverage probability is calculated for a given SNR threshold, τ, as

$$\mathbb{P}_{cov}(\tau) = \mathbb{P}(SNR_{\zeta} > \tau). \tag{4.3}$$

Similarly, we define rate coverage probability at a given rate threshold,γ, as

$$\mathbb{P}_{rate}(\gamma) = \mathbb{P}(rate > \gamma) = \mathbb{P}(SNR_{\zeta} > 2^{\frac{\gamma \times M}{B} - 1}). \tag{4.4}$$

4.2 UAVs with Pre-existing Terrestrial Cellular Infrastructure

For performance analysis of our system we consider a time division multiple access (TDMA) scheme in our network. The user will connect to any tier based on already discussed user association scheme. For a user connected to UHF tier, there will be no interference as we have assumed only a single MBS in the RoI. Therefore, for every user connected to the MBS, the signal-to-interference and noise ratio (SINR) will be calculated as

$$SINR_U = \frac{P_{rx,U}}{\sigma_U^2}, \tag{4.5}$$

where the noise power, in dBs, is calculated as $\sigma_U^2 = -174 dBm/Hz + 10 log(B_U) + NF$, and NF is the noise figure of receiver. We have assumed that there is only one MBS in the RoI, therefore interfernce is assumed to be zero in the UHF tier. Suppose, n_u, is the number of users connected to the UHF tier or the MBS. For each user connected to the MBS the downlink rate received will be

$$R_U = \frac{B_U}{n_u} log_2(1 + SINR_U), \tag{4.6}$$

where B_U is the total bandwidth available at the MBS.

The user will connect to mmWave tier only if maximum average biased received power from either SBS or UAV is greater than power received from MBS which is operating in UHF spectrum. In that case, the connected SBS or UAV will be serving base station while the remaining will act as interferers. However, it is to be noted that SBS and UAVs are operating at different mmWave spectrums of 73GHz and 28GHz, respectively. Therefore, for user connected to a SBS, only the remaining SBSs will act as interferers. Similarly, for a user connected to a UAV, interference will come only from remaining UAVs. The signal-to-interference and noise ratio (SINR) for the mmWave tier is given by

$$SINR_\upsilon = \frac{P_{rx,\upsilon}}{\sum_I P_I + \sigma_\upsilon^2}, \quad \upsilon \in \{SBS, UAV\} \tag{4.7}$$

where P_I is the sum of powers received from all interfering base stations which depends upon user link established with either a SBS or a UAV. The downlink data rates received by each user in the mmWave tier will be given by

$$R_\upsilon = \frac{B_\upsilon}{n_\upsilon} log_2(1 + SINR_\upsilon). \tag{4.8}$$

Now that we have calculated SINR and downlink data rates for each user, we evaluate the performance of our HetNet by defining two parameters, i.e., SINR coverage and rate coverage. The SINR coverage, at a given threshold τ, is given by

$$\mathbb{P}_{cov}(\tau) = \mathbb{P}(SINR_{\zeta} > \tau). \tag{4.9}$$

Similarly, for a given rate threshold,Γ, the rate coverage probability is defined as

$$\mathbb{P}_{rate}(\Gamma) = \mathbb{P}(rate > \Gamma) = \mathbb{P}(SINR_{\zeta} > 2^{\frac{\Gamma \times n_{\zeta}}{B}-1}). \tag{4.10}$$

Chapter 5

Results and Discussions

Performance analysis of our proposed system model is done through monte carlo simulations using the software Matlab® 2018a.

5.1 Standalone UAVs Network

To evaluate performance of the hybrid HetNet, we model a system as per already defined parameters with equal number of UAVs operating at sub-6GHz and mmWave. Monte carlo simulations are carried out to analyze the network. Simulation parameters given in Table 5.1 were used. We first analyze the SNR and per user data rates of the system with different values of bias factor for mmWave tier. Reason for biasing users towards mmWave tier is to compensate for higher path loss of mmWave, so that maximum users can associate with mmWave UAVs. Through this we can increase per user data rates and meet network QoS requirements, if any.

Fig. 5.1 depicts SNR coverage probability for the hybrid network. Equal

Table 5.1: Simulation Parameters: Standalone UAVs network

Parameter	Value	Parameter	Value
$f_{c,U}$	2.4GHz	$f_{c,mm}$	28GHz
BW_U	20MHz	BW_{mm}	2GHz
$P_{tx,U}$	30dBm	$P_{tx,mm}$	30dBm
$BeamWidth_U$	90^o	$BeamWidth_{mm}$	30^o
Environment	$a = 9$, $b = 0.11$	Std ($\chi_{L,mm}$)	5.2
η_{los},η_{nlos}	1 , 20	Std($\chi_{N,mm}$)	7.2
NF	$9dB$	$\alpha_{L,mm}$,$\alpha_{N,mm}$	2 , 3.3
users	200	Nakagami, (m_L,m_N)	5 , 1
Ht, ABS_U	100 m	Ht, ABS_{mm}	30 m

number of sub-6GHz and mmWave UAVs are deployed in the network. The SNR performance is evaluated at different bias factor values for mmWave tier. Coverage performance of system is best when there is no bias factor. The reason is that sub-6GHz frequencies have better propagation properties due to which received power is higher. Without biasing any tier, maximum users will associate with sub-6GHz tier and SNR coverage of the network is high. However, as we offload users towards mmWave tier through biasing, SNR coverage of the HetNet degrades. This is because, received power from mmWave UAVs will always be lower due to higher path loss experienced at mmWave frequencies. As more users associate with mmWave tier, the SNR coverage of the network reduces. As mmWave bias factor, β_{mm}, increases from $0dB$ to $30dB$, SNR coverage probability, at $\tau = 0dB$, drops from 1 to 0.83. For lesser bias factor values of $10dB$ and $20dB$, the SNR coverage probabilities are higher, i.e., 0.98 and 0.92, respectively. This illustrates that the more we force users to associate with mmWave tier using higher value of bias factor, the lesser will be the SNR coverage for the HetNet. However Fig. 5.2 shows us the benefit, in terms of meeting QoS metric of data rate, if

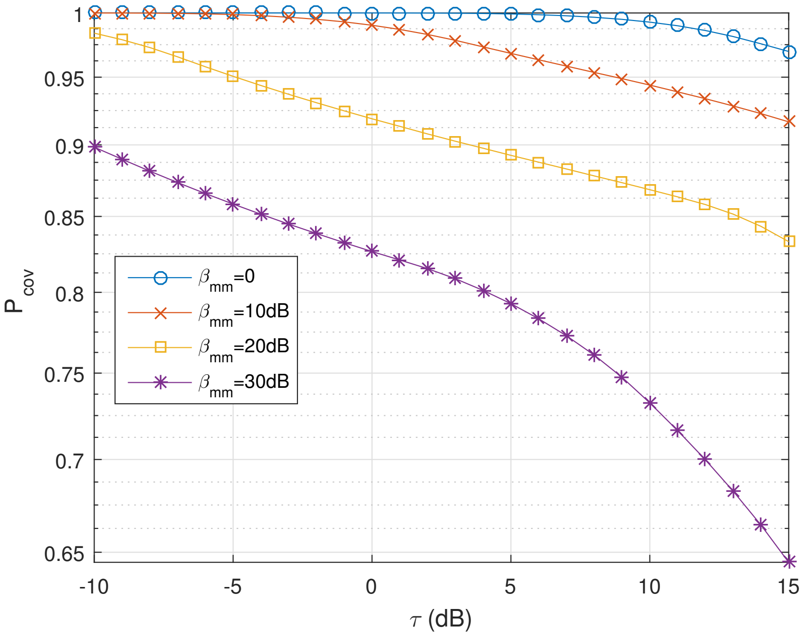

Figure 5.1: SNR coverage probability ($N = 20$, $N_U = 10$,$N_{mm} = 10$,$n = 200$)

we use higher bias factor for mmWave tier. At rate threshold of $\gamma = 1Mbps$, data rate coverage for the HetNet with no bias increases from 0.50 to 0.85 when $30dB$ bias factor for mmWave tier is used. The reason is that a larger spectrum available at mmWave tier helps improve the QoS in terms of data rates for each user associated with it.

Fig. 5.3 shows the variation in rate coverage probability as the number of users, n, in the RoI increases. The network is heavily biased, $\beta_{mm} = 30dB$, towards the mmWave tier as we want to satisfy the QoS metric of data rates. Considering $\gamma = 1Mbps$ as rate threshold, for 100users, the network can satisfy QoS metric for all the users, however, user satisfaction will drop to almost 50% if users increase from 100 to 400. The reason for drop in rate coverage is that in TDMA scheme, the UAV divides available bandwidth

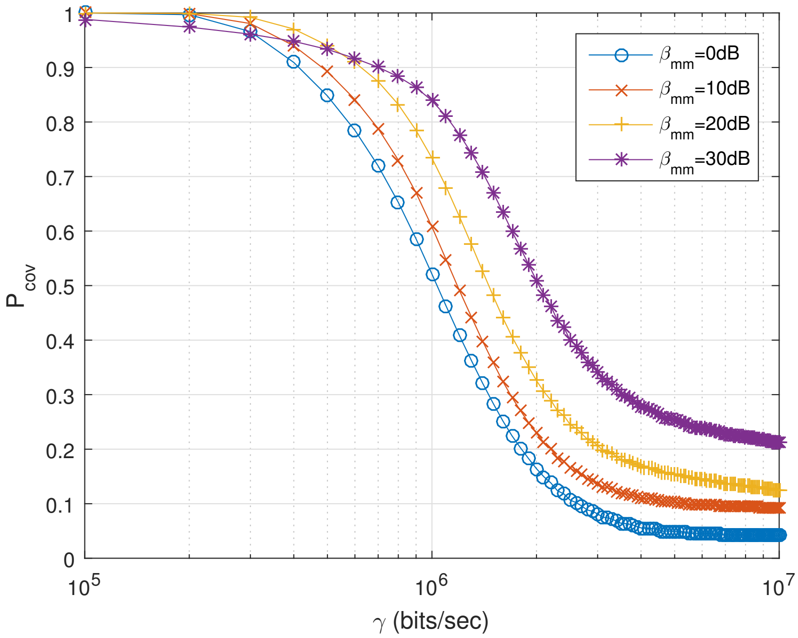

Figure 5.2: Rate coverage probability ($N = 20$, $N_U = 10$,$N_{mm} = 10$,$n = 200$)

equally among the number of users associated with it. As users in the area increase, the bandwidth resource is allocated to more users resulting in drop in individual user data rates.

If we want to satisfy the coverage requirements then it is favourable that more users associate with sub-6GHz tier. However, if we want to fulfill rate requirements then we want maximum users to associate with mmWave tier. For this we need to offload users from sub-6GHz tier to mmWave tier through biasing. Bias factor is used to compensate for higher path loss at mmWave frequencies for user association purpose. From Fig. 5.4 we quantify maximum number of users that can be offloaded towards mmWave UAVs. Keeping number of users, $n = 200$, and number of UAVs, $N = 20$, constant, we vary the ratio of mmWave UAVs to total UAVs, ϵ, and the mmWave tier bias,

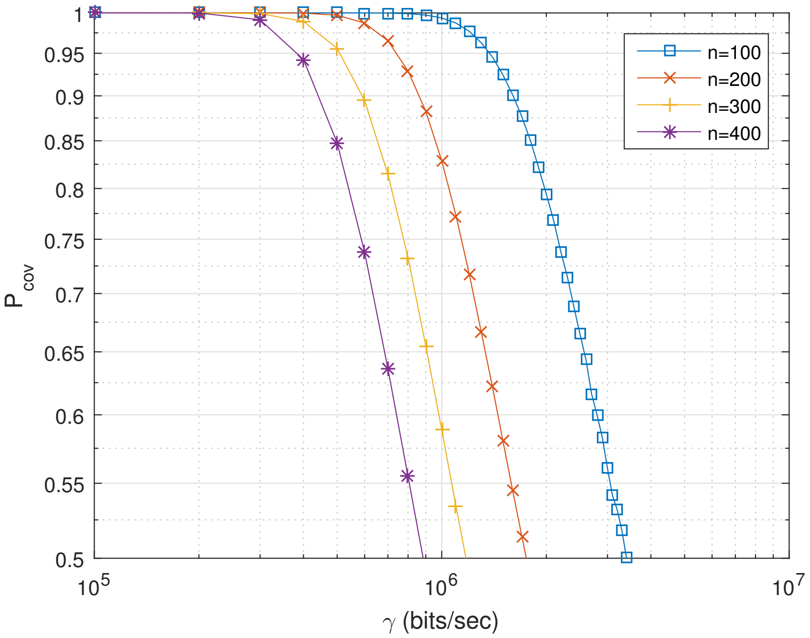

Figure 5.3: Rate coverage probability related to number of users, n ($N = 20$,$N_U = 10$, $N_{mm} = 10$,$\beta = 30dB$)

β_{mm}. If we have only two mmWave UAVs in the network, $\epsilon = 0.1$, then even if we use bias factor $30dB$ for mmWave, only 7% of users will associate with mmWave UAVs. However, if we increase ratio of mmWave UAVs in network, $\epsilon = 0.9$, then we can associate up to 65% users with mmWave UAVs.

The advantage of mmWave tier biasing can be observed in Fig. 5.5 where the QoS metric of the network is rate coverage. We want to see how many users can be provided with required data rates with fixed number of UAVs, $N = 20$. We keep the mmWave bias fixed at $30dB$. Reason for high bias is that, rate being the QoS metric, we want to associate maximum users with mmWave UAVs. Now we analyze the HetNet by varying fraction of mmWave UAVs as well as the number of users in the network and observe coverage

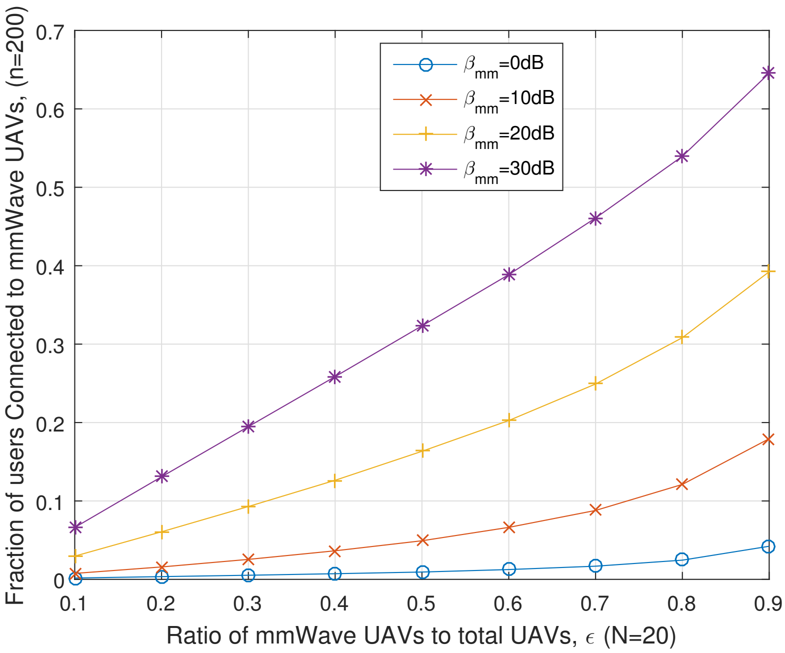

Figure 5.4: Fraction of users connected to the mmWave tier ($n = 200$, $N = 20$)

trends for users getting above $1Mbps$. For various user densities, the number of users satisfying QoS metric of rate increases considerably with an increase in ratio of mmWave UAVs to total UAVs, ϵ. Taking 200 users as a reference, the percentage of users above $1Mbps$ increases from 63% to 100% as ratio of mmWave UAVs in network, ϵ, increases from 0.1 to 0.9. The reason is that for meeting high data rate requirements, ratio of mmWave UAVs as well as the fraction of users associated with mmWave UAVs in the network should increase. We also gain insight into the network capacity by increasing the number of users. If want to fulfill rate requirements for 80% users than the network can support 300 users with ratio of mmWave UAVs to total UAVs, $\epsilon = 0.8$. Which means that we need 16 mmWave UAVs out of 20 UAVs in

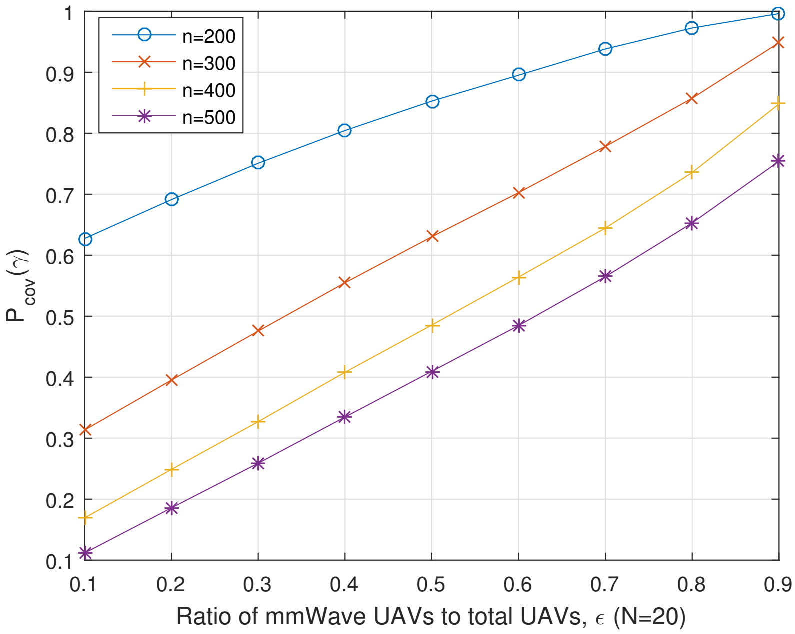

Figure 5.5: Rate coverage trends for users satisfying QoS metric of $\gamma > 1Mbps$ ($N = 20$, $\beta mm = 30dB$)

the network to meet rate QoS.

Fig. 5.6 shows the enhancement in data rates as users offload towards mmWave UAVs due to effects of bias parameter, β_{mm}. As we increase β_{mm} from $0dB$ to $30dB$ the number of users receiving rates above $2Mbps$ increase from almost 14% to 50%. As we have kept number of UAVs fixed, $N = 20$, and number of mmWave and sub-6GHz UAVs equal, $\epsilon = 0.5$, therefore this improvement has been achieved only through offloading users towards mmWave tier without varying any other network parameter or configuration.

Sub-6GHz and mmWave bring contrasting characteristics to the HetNet. To gain valuable insight into the under study HetNet, in Fig. 5.7, we compare the coverage and rate trends with different biasing values, β_{mm}, and ratios

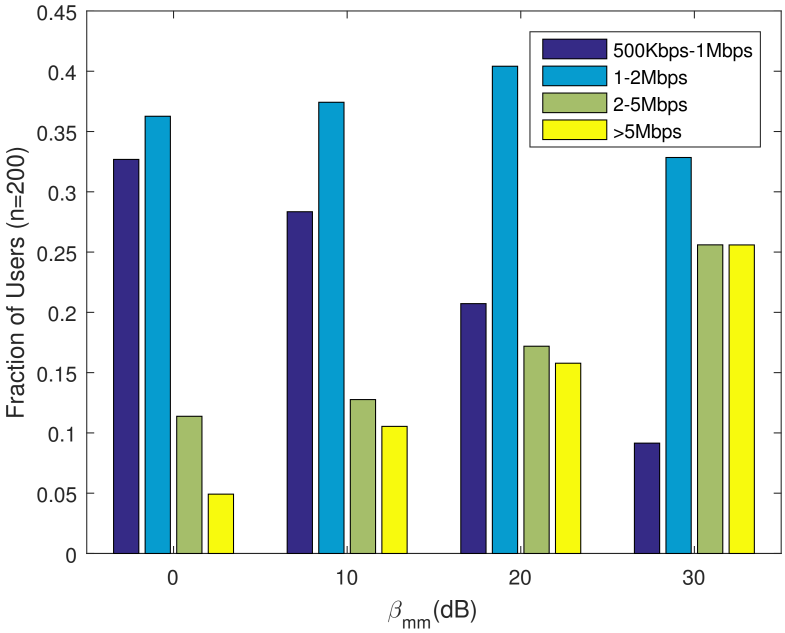

Figure 5.6: Rate trends for users with different bias factor ($n = 200$, $N = 20$, $N_U = 10$, $N_{mm} = 10$)

for mmWave UAVs, ϵ. To explain the inherent coverage-rate trade-off in the network we take $\epsilon = 0.3$ as reference and check the SNR coverage probabilities for various biasing values of mmWave tier. At $\epsilon = 0.3$, SNR coverage corresponds to 0.99, 0.95 and 0.9 for mmWave biasing values of $10dB$, $20dB$, and $30dB$, respectively. Keeping same ratio of mmWave UAVs, $\epsilon = 0.3$, rate coverage at $\gamma = 1Mbps$, corresponds to 0.5, 0.67 and 0.76 at bias factor values of $10dB$, $20dB$, and $30dB$ respectively. This depicts behavior of the HetNet in which SNR coverage degrades as more users offloads towards mmWave UAVs or ratio of mmWave UAVs to total UAVs in the network, ϵ, increases and vice versa. On the other side, rate coverage of the network improves as we increase ratio of mmWave UAVs in the network or bias more

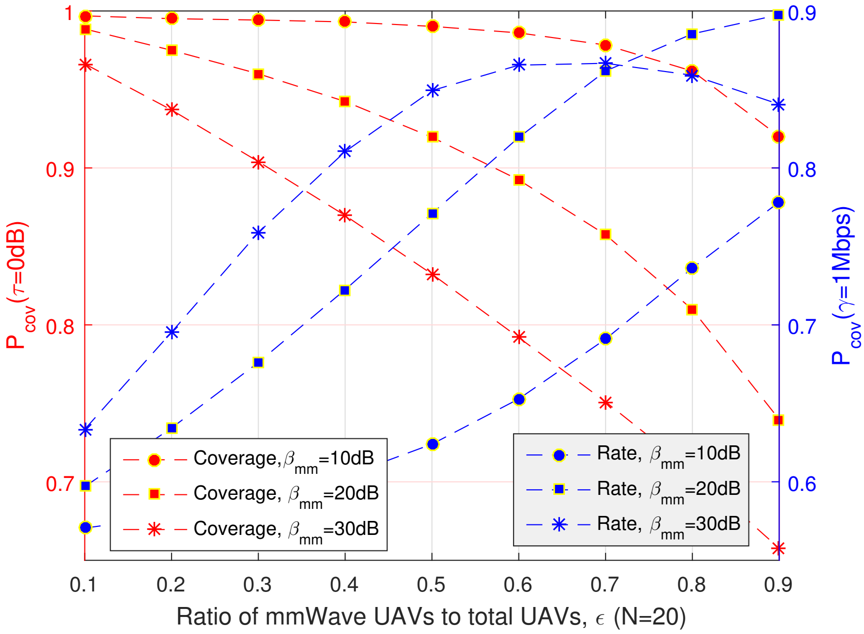

Figure 5.7: SNR and rate coverage trends for different bias factor ($\tau = 0dB, \gamma = 1Mbps, N = 20, n = 200$)

users towards mmWave tier. This implies, that we can tune the configuration and parameters of the HetNet in accordance with the network QoS requirements. If coverage is the priority than we dominate network with sub-6GHz frequencies, but if rate is the QoS metric than mmWave frequencies should play a major role in the network. From Fig. 5.7, we observe that at $\epsilon = 0.6$, we get the maximum rate coverage in HetNet for bias factor value of $30dB$. Further increase in fraction of mmWave UAVs will not improve the network QoS in terms of data rate. The reason is that the available mmWave spectrum will be further divided between the mmWave UAVs and too many users receiving low powers from mmWave UAVs will associate with mmWave tier due to higher value of bias factor. In the HetNet, there needs to be an ideal

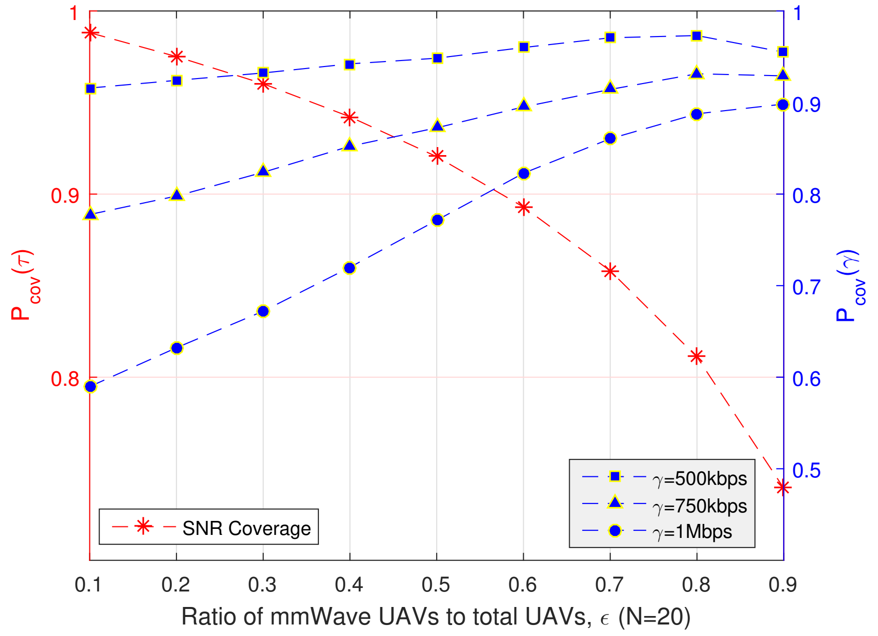

Figure 5.8: Variation in SNR and rate coverage and rate coverage ($N = 20$, $\beta_{mm} = 20dB, \tau = 0dB$)

distribution between users associated with sub-6GHz tier and mmWave tier to satisfy QoS metrics of coverage and data rates. We observe that at bias factor value of $30dB$, if 60% UAVs operate on mmWave band, then we will get optimum QoS in terms of data rates. Beyond that network performance will degrade. However if we use bias factor value 0f $20dB$ then we get an increase in rate coverage as we keep on increasing fraction of mmWave UAVs upto $\epsilon = 0.9$. The reason is that keeping $\beta_{mm} = 20dB$ keeps the HetNet more balanced in terms of user distribution between the two tiers. We also realize that better coverage-rate trade off can be achieved with bias factor value of $20dB$. At 60% mmWave UAVs in the Network and $\beta_{mm} = 20dB$, the SNR coverage is almost 90% and the rate coverage is 83%.

As an example we demonstrate adjustment of network configuration and parameters through Fig. 5.8. The SNR coverage is plotted along with the rate coverage at three different thresholds, $\gamma = 500Kbps$, $750Kbps$ and $1Mbps$. We consider that our QoS metrics are both coverage and rates, therefore to experience a slow decay in SNR coverage, we use a slightly conservative biasing value of $20dB$ for this result. From figure we observe that when 50% of the UAVs are mmWave, SNR coverage is satisfied for 93% users while 78% users are above the rate threshold of $1Mbps$ and 87% users satisfy rate coverage at $750Kbps$. This illustrates that how we can efficiently design a HetNet based on varying QoS metrics. If QoS required is SNR coverage, then we increase the UAVs operating in sub-6GHz range, however if QoS metric is user data rates, then we increase the number of UAVs operating at mmWave frequencies.

5.2 UAVs with Pre-existing Terrestrial Cellular Infrastructure

For simulation of our system model, we model a system with single MBS at the centre of RoI and with equal number of SBS and UAVs in the mmWave tier. For analysis purpose we carry out monte carlo simulations. Table 5.2 defines simulation parameters for our system model. We analyse performance of the HetNet on already defined metrics of SINR and rate coverage. Different bias factor values, β_{mm}, are used to offload maximum users towards the mmWave tier.

Table 5.2: Simulation Parameters: UAVs with terrestrial Cellular Network

Parameter	Value	Parameter	Value
$f_{c,U}$	2.4GHz	$f^{SBS}_{c,mm}$,$f^{UAV}_{c,mm}$	73GHz , 28GHz
B_U	20MHz	B_{mm}	400MHz
$P_{tx,U}$	40dBm	$P_{tx,mm}$	30dBm
θ^{UAV}_{mm}	30^o	θ^{SBS}_{mm}	30^o
Environment	$a = 9$, $b = 0.11$	Std ($\chi_{L,mm}$)	5.2
users	500	Std($\chi_{N,mm}$)	7.2
NF	$9dB$	$\alpha_{L,mm}$,$\alpha_{N,mm}$	2 , 3.3
α	3	χ_u	4
Ht, UAV	$30m$	$N_{SBS} = N_{UAV}$	20

Fig. 5.9 shows the SINR coverage probability for the HetNet. The HetNet consists of a UHF MBS and mmWave SBSs and UAVs. The results are obtained at different bias factor values for mmWave tier. The reason is that power received from UHF tier will always be greater due to much better propagation characteristics. On the contrary mmWave encounters much higher losses due to propagation and blockages. As our user association with base station is dependent upon maximum power therefore without using bias factor for mmWave tier, the majority of users will associate with MBS. This will not only overload the MBS, but also reduce the advantage that mmWave SBS and UAVs offer in terms of data rates. Association based on maximum average biased received power means that even if power received from mmWave tier is slightly lower than UHF tier, depending upon the bias factor value, the user will still associate with the mmWave tier. From Fig.2, we observe that as bias factor value is increased, the overall coverage of the HetNet reduces. However at $\beta_{mm} = 15dB$, and $\tau = -5dB$, the network SINR coverage is still well above 0.9.

The real advantage of offloading users towards mmWave tier can be ob-

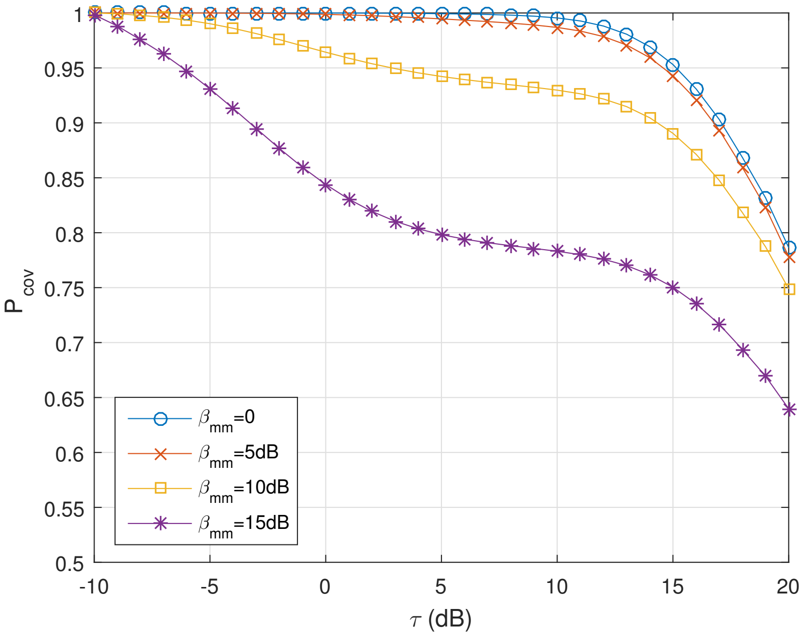

Figure 5.9: SINR coverage probability related to bias factors, ($MBS = 1$, $N_{SBS} = 20$, $N_{UAV} = 20$)

served in Fig. 5.10 when we see the rate coverage of the HetNet. As value for β_{mm} increases, user association with mmWave tier will start to increase and the network will be able to exploit the huge bandwidth available at mmWave tier. From Fig. 3, we can see that if do not use bias factor value for mmWave tier, then, at rate threshold of $\Gamma = 1Mbps$ as low as 5% of users are receiving data rates of $1Mbps$ and above. Considering by modern smart city standards this is very low. However, when we use bias factor value, $\beta_{mm} = 15dB$, users receiving data rates in excess of $1Mbps$ increases to 27%. Which means that we have achieved almost 5 times increase in number of users achieving required data rates.

Fig. 5.11 shows the advantage of deploying mmWave UAVs to assist

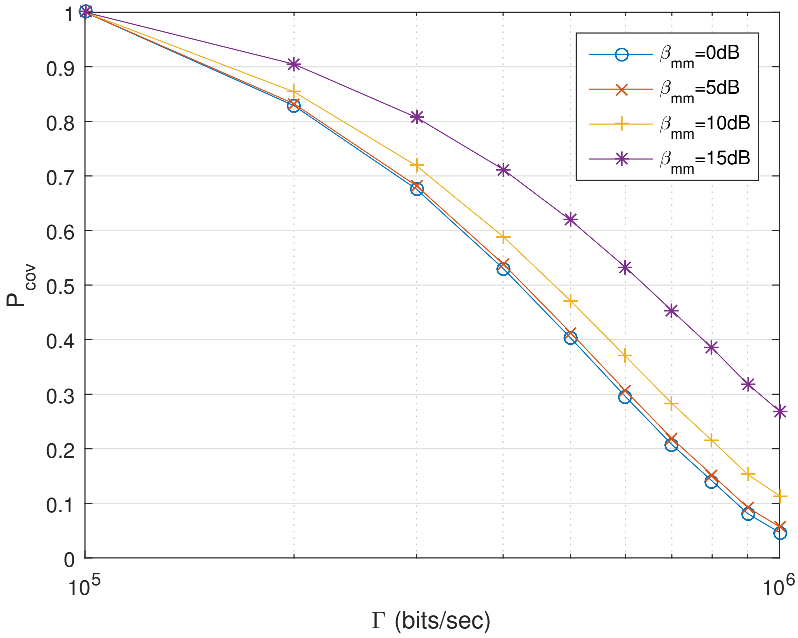

Figure 5.10: Rate coverage probability related to bias factors, (n = 500, $MBS = 1$, $N_{SBS} = 20$, $N_{UAV} = 20$)

the terrestrial cellular infrastructure. A bias factor value of $15dB$ has been used for the mmWave tier so that traffic can be offloaded from MBS to the SBSs and UAVs. When there are no UAVs deployed and only ground based MBS and SBS are providing communication services the user data rates have dropped considerably. This is due to the fact that number of users have increased considerably and the existing communication resources are not sufficient to meet the data rates requirements. When we deploy mmWave UAVs in the area, then the average data rates increases in the RoI. As we increase the number of mmWave UAVs, N_{UAV}, from 10 to 40, the number of users receiving data rates of $1Mbps$ and above increases from 10% to 42%.

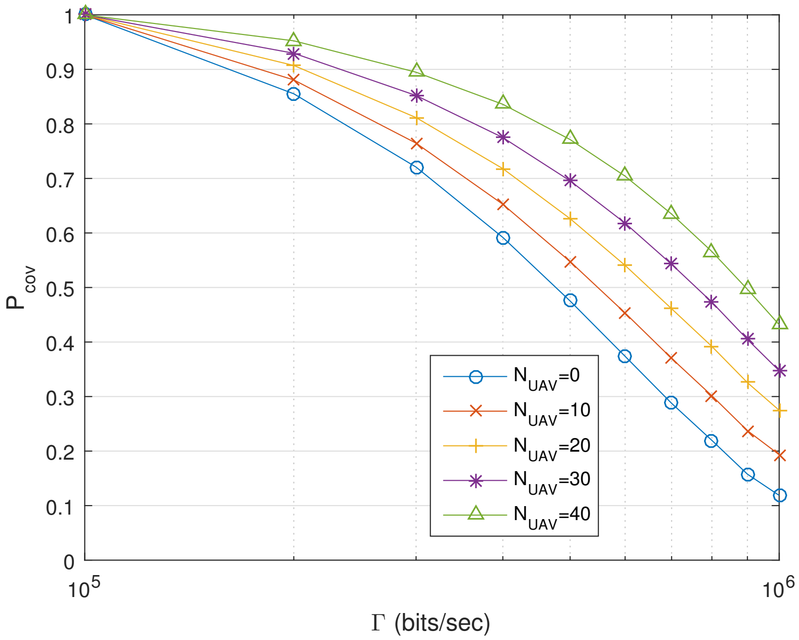

Figure 5.11: Rate coverage probability related to number of UAVs, ($n = 500$, $MBS = 1$, $N_{SBS} = 20$, $\beta_{mm} = 15dB$)

Chapter 6

Conclusion & Future Works

6.1 Concluding Notes

Future communication networks will require huge bandwidth and network resources to sustain its operations and meet QoS requirements of its users. The networks will be interlaced with multitude of IoT sensors which will put additional load on the network. As 5G and beyong networks emphasize on hyper connectivity and integration, therefore mmWave UAVs offer a cost effective, flexible and rapid solution for meeting any network requirement. Efficient placement of UAVs inside the networks will enhance capacity of existing network in an effective manner. Moreover, through effective placement of UAVs based on user and network demands we can further enhance communication service provisioning.

To meet QoS of bandwidth hungry applications, integration of mmWave with aerial platforms is indispensable. However, due to propagation losses and high directionality required to cater for those losses, stand alone mmWave network will always have coverage holes in the network. As a practical alternative, we proposed Hybrid HetNets consisting of sub-6GHz and mmWave UAVs. Where sub-6GHz UAVs will enhance effective SNR coverage and mmWave UAVs will enhance network capacity in terms of data rates. However, adjustment of network configuration will be required to meet peculiar QoS requirements in terms of rate and coverage. We summarize the work done in this thesis as follows

1. A UAV-assisted 5G HetNet has been designed in which sub-6GHz and mmWave UAVs co-exist.
2. QoS based performance analysis of a standalone UAVs network has been carried out. QoS metrics are coverage and data rates.
3. Coverage and rate trade-off has been analyzed in a HetNet constituting of both mmWave and UHF UAVs. The diverse characteristics that mmWave and UHF spectra brings into a network have been effectively analyzed.
4. A method has been proposed, whereby, the HetNet can be tuned by varying parameters such as bias factor and fraction of mmWave UAVs to total UAVs in the HetNet to meet the user QoS requirements in terms of coverage and rates.
5. In areas where there is an already existing terrestrial cellular infrastructure, the effects of mmWave UAVs in terms of capacity enhancement of the network have been studied.

6.2 Future Works

As a future addition to our work, coverage and capacity of the network, particularly in mmWave tier, can be further improved through advance beam forming and beam scanning techniques. Moreover, we can exploit mobility of UAVs by using a cost function based placement method for UAVs. Through efficient UAV placement operation we can position a UAV at a spot where there is requirement to enhance the network in terms of data rate. Also, by obtaining real time information about user locations UAV can be positioned at a crowded hotspot where the existing terrestrial base stations are overloaded and can not facilitate the huge number of users. The efficiency and performance of the HetNet can be further enhanced using a dynamic resource allocation scheme based on user requirements. Whereby, only users with higher bandwidth requirements will connect to mmWave UAV. Such a scheme will further enhance the QoS provisioning in the network.

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