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QoS-based Performance Analysis of mmWave UAV-assisted 5G Hybrid Heterogeneous Network

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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 future fifth generation (5G) and Internet of things (IoT) networks. In this study, we consider a downlink scenario in a multi-tier heterogeneous network (HetNet), with sub-6GHz and millimeter wave (mmWave) UAVs coexisting as aerial base stations (ABSs), to meet the network quality-of-service (QoS) requirements. The considered QoS metrics are network coverage and data rates. The network area has no pre-existing communication infrastructure. We study the impact of various network configurations, by varying ratio of mmWave UAVs to total UAVs in the HetNet, number of users, and bias factor for mmWave tier. Our results validate that sub-6GHz and mmWave UAVs can be deployed together to complement each other in a multi-tier HetNet where the sub-6GHz tier will enhance the coverage and the mmWave tier will improve the data rates. Through extensive simulations, we propose and implement a methodology to configure the HetNet for an efficient coverage-rate trade off, while meeting the desired QoS metrics at the same time.**

***Index Terms*—5G Networks, mmWave, UAV-assisted, heterogeneous networks (HetNets), hybrid network**

I. INTRODUCTION

To keep up with the increasing diversity of communication networks, 5G and beyond network architectures need to become more heterogeneous, diverse and flexible. 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 the networks in keeping up with the ever increasing user demands and scenarios [1].

Provision of abilities such as rapid mobility and flexibility makes aerial base stations (ABSs) an important building block for the next generation network architecture. Existing literature on UAV communication has focused on multiple aspects ranging from the 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 [2]. However, owing to power constraints and payload restrictions, we envisage a role for 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 [3] 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 [4] exploited mobility of UAVs to determine optimal 3-D deployment of UAVs to maximize downlink coverage by using circle packing theory. Authors in [5] give a novel method for UAV deployment depending upon a cost function-based neural network which allocates the UAVs to areas with high traffic demands. Such an arrangement not only enhances the coverage and capacity of the network, but also balances load and offloads terrestrial base stations in ultra dense networks. In [6], the 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 the ground base stations and UAVs are distributed according to Poisson Point Processes (PPPs). Users are modeled through Poisson Cluster Process (PCP) around the ground projection of UAVs. However, multiple clusters of users around fixed points is a rare phenomenon in actual network scenarios. [7] optimizes the effectiveness of UAVs for providing back haul connectivity between small cells and the core network.

Although, UAVs operating at sub-6GHz have dominated most of the research, recently the trend is shifting towards deployment of millimeter wave (mmWave) UAVs. Deployment of mmWave UAVs for public safety communications has been proposed in [8]. The reason for above 6GHz frequencies is that a larger available spectrum of mmWave allows to meet the bandwidth requirements of critical applications. The enhanced LoS capability of UAV makes it useful for being deployed as a mmWave communication platform. Increased path loss of mmWave with distance were considered as a challenge for mmWave communication from UAVs, however directionality of mmWave can be used to compensate for the path loss [9]. In [10], 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 the directivity of mmWave causes a considerable increase in SIR.

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. 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 the network performance.

II. SYSTEM MODEL

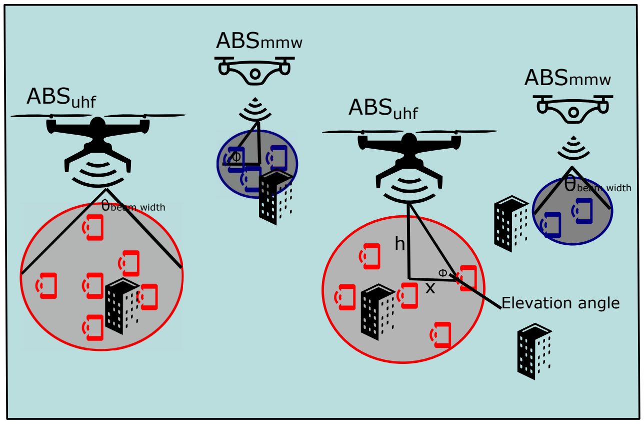


Figure 1: System model of heterogeneous network

We consider a scenario, shown in Fig. 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, $\delta min = 30$m, 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 term ϵ as the number of mmWave UAVs to the total number of UAVs in the HetNet, i.e., $\epsilon = \frac{N_{mm}}{N}$.

A. 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 the geometric LoS probability model as derived in [3]. 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

$$\phi_\zeta = \arctan\left(\frac{h_\zeta}{x_\zeta}\right), \quad \zeta \in \{U, mm\}, \tag{1}$$

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 [3], i.e,

$$PLoS_\zeta = \frac{1}{1 + a\exp(-b[\phi_\zeta - a])}, \tag{2}$$

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

$$PNLoS_\zeta = 1 - PLoS_\zeta. \tag{3}$$

After we have determined the PLoS and PNLoS based on (1)-(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

$$L_U = PL_U + (PLoS \times \eta_{LoS}) + (PNLoS \times \eta_{NLoS}), \tag{4}$$

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

$$PL_U = 20\log\left(\frac{4\pi f_{c,U} d_U}{c}\right), \tag{5}$$

where $f_{c,U}$ is the 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 the path loss as

$$L_{mm}(d) = \begin{cases} \rho + 10\alpha_L \log(d_{mm}) + \chi_L & \text{LoS link,} \\ \rho + 10\alpha_N \log(d_{mm}) + \chi_N & \text{otherwise,} \end{cases} \tag{6}$$

where ρ is the fixed path loss given by $\rho = 32.4 + 20\log(f_{c,mm})$ 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 the link is LoS or NLoS. As we have used probabilistic model for calculating the geometric LoS, we therefore use weighted averaging for calculating the path loss of a mmWave link based on PLoS and PNLoS from (2) and (3) as

$$L_{mm} = PLoS_{mm} \times L_{mm,L} + PNLoS_{mm} \times L_{mm,N}. \tag{7}$$

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

$$P_{rx,\zeta} = P_{tx,\zeta} + G(\theta_\zeta) + \mu_\zeta - L_\zeta, \tag{8}$$

where μ_ζ denotes the multipath fading depending upon whether the 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 the multipath fading envelope value based on the probabilistic values for LOS and NLoS for sub-6GHz and mmWave link as

$$\mu_\zeta = (PLoS_\zeta \times \mu_{\zeta,L}) + (PNLoS_\zeta \times \mu_{\zeta,N}). \tag{9}$$

We calculate the antenna gain, which is given as

$$G(\theta_\zeta) = \frac{2}{1 - \cos[\theta_\zeta/2]}, \tag{10}$$

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

B. 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

$$P_{avg\ rx,\zeta} \ = P_{tx,\zeta} + G(\theta_\zeta) - PL_\zeta + \beta_{mm}, \tag{11}$$

where $P_{avg\ rx,\zeta}$ is the average biased 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 whichever link gives maximum value from (11), a user will connect to that UAV. The bias factor is an important parameter which helps us in offloading the users from sub-6GHz tier to the mmWave tier based on the network and user requirements.

III. PERFORMANCE ANALYSIS

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,

$$SNR_\zeta = \frac{P_{rx,\zeta}}{\sigma_\zeta^2}, \tag{12}$$

we calculate the noise power (dB) as $\sigma_\zeta^2 = -174\text{dBm/Hz} + 10\log(B_\zeta) + NF$, 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,

$$R_\zeta = \frac{B_\zeta}{M}\log_2(1 + SNR_\zeta). \tag{13}$$

We define the 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

$$\mathbb{P}_{cov}(\tau) = \mathbb{P}(SNR_\zeta > \tau). \tag{14}$$

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

$$\mathbb{P}_{rate}(\gamma) = \mathbb{P}(rate > \gamma) = \mathbb{P}(SNR_\zeta > 2^{\frac{\gamma \times M}{B}} - 1). \tag{15}$$

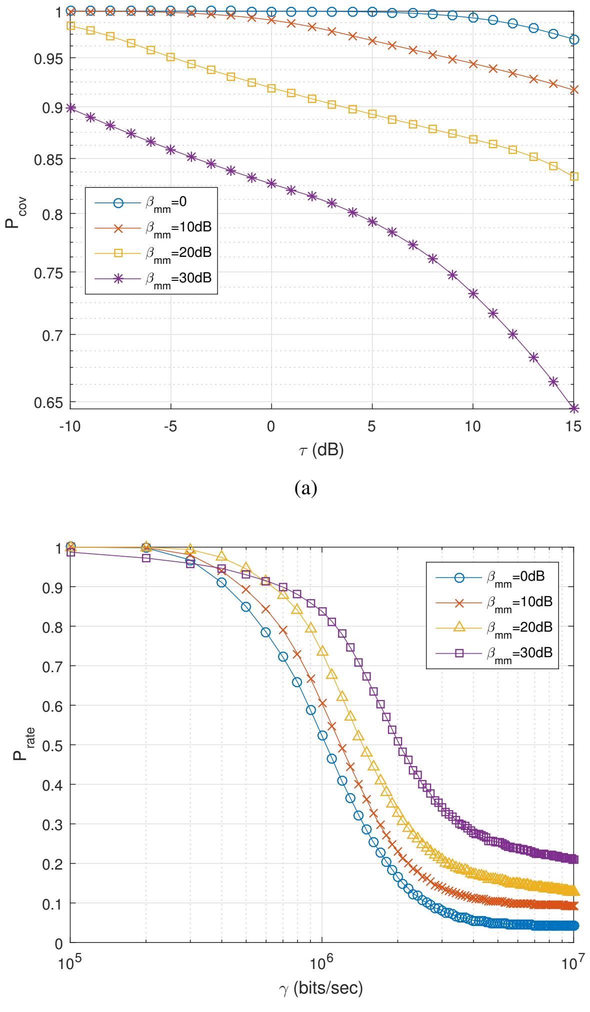
A. Simulation and Results

To evaluate performance of the hybrid HetNet, we model a system as per the 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 I were used. We first analyze the SNR and per user data rates of the system with different values of bias factor for the mmWave tier. Reason for biasing users towards the mmWave tier is to compensate for the higher path loss of mmWave, so that maximum users can associate with mmWave UAVs. Through this we can increase the per user data rates and meet the network QoS requirements, if any.

Table I: Simulation Parameters

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

Fig. 2(a) depicts the SNR coverage probability for the hybrid network. Equal number of sub-6GHz and mmWave UAVs are deployed in the network. The SNR performance is evaluated at different bias factor values for the mmWave tier. The coverage performance of the network is best when there is no bias factor. The reason is that sub-6GHz frequencies have better propagation properties due to which the received power is higher. Without biasing any tier, maximum users will associate with the sub-6GHz tier and SNR coverage of the network will be high. However, as we offload users towards mmWave tier through biasing, SNR coverage of the HetNet degrades. This is because, the 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 τ =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 the mmWave tier using higher value of bias factor, the lesser will be the SNR coverage for the HetNet. However Fig. 2(b) shows us the benefit, in terms of meeting QoS metric of data rate, if



(a)

(b)

Figure 2: SNR and rate coverage probability ($N = 20$, $N_U = 10$, $N_{mm} = 10$, $n = 200$)

we use higher bias factor for mmWave tier. At rate threshold of γ =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. 3 shows the variation in rate coverage probability as the number of users, n, in the RoI increases. The network is heavily biased, β_{mm} =30dB, towards the mmWave tier as we want to satisfy the QoS metric of data rates. Considering γ =1Mbps as the rate threshold, for 100 users, 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 the TDMA scheme, the UAV divides available bandwidth 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 the individual user data rates.

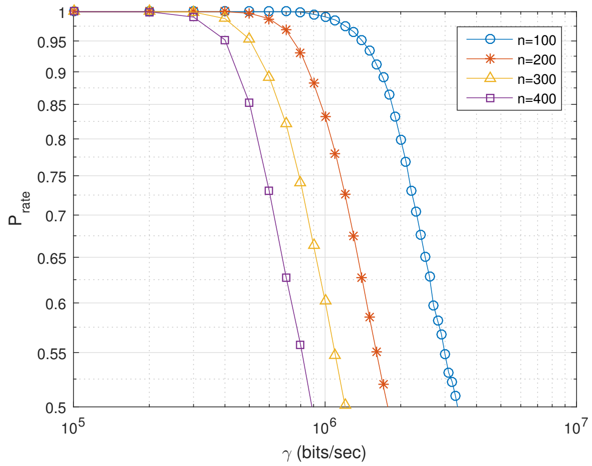


Figure 3: Rate coverage probability related to number of users, n ($N = 20$, $N_U = 10$, $N_{mm} = 10$, $\beta = 30dB$)

If we want to satisfy the coverage requirements then it is favorable that more users associate with the sub-6GHz tier. However, if we want to fulfill rate requirements then we want maximum users to associate with the 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. 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, 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 the ratio of mmWave UAVs in network, $\epsilon = 0.9$, then we can associate up to 65% users with mmWave UAVs.

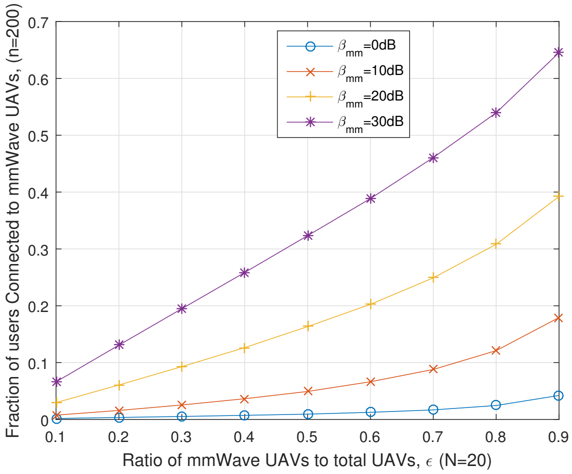


Figure 4: Fraction of users connected to the mmWave tier ($n = 200$, $N = 20$)

The advantage of mmWave tier biasing can be observed in Fig. 5 where the QoS metric of the network is rate coverage. We want to see how many users can be provided with the required data rates with fixed number of UAVs, $N = 20$. We keep the mmWave bias fixed at 30dB. The 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 the coverage trends for users getting above 1Mbps. Fig. 5 illustrates that 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 88% as ratio of mmWave UAVs in network, ϵ, increases from 0.1 to 0.6. 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. However, after a particular threshold point the rate coverage starts to drop. The reason is that after a specific value of ϵ, based upon the number of users in the HetNet, increasing the number of mmWave UAVs further in the network will increase the number of users going into cellular outage. This will cause a drop in the average data rates received in the HetNet. We also gain insight into the network capacity by increasing the number of users. If want to fulfil the rate requirements for 80% users then the network can support 300 users with ratio of mmWave UAVs to the total UAVs, $\epsilon = 0.7$. Which means that we need 14 mmWave UAVs out of 20 UAVs in the network to meet the rate QoS.

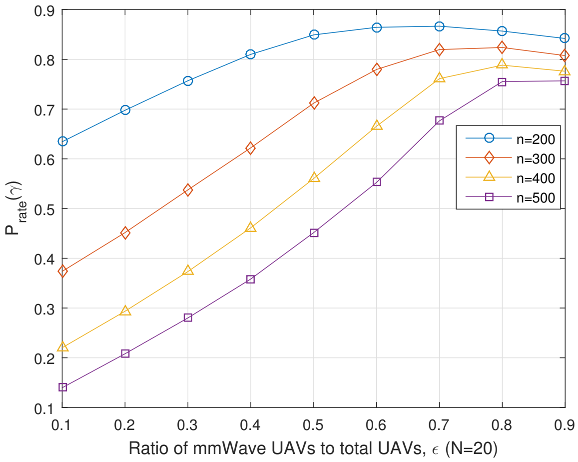


Figure 5: Rate coverage trends for users satisfying QoS metric of $\gamma > 1Mbps$ ($N = 20$, $\beta mm = 30dB$)

Fig. 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 the number of UAVs fixed, $N = 20$, and the 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.

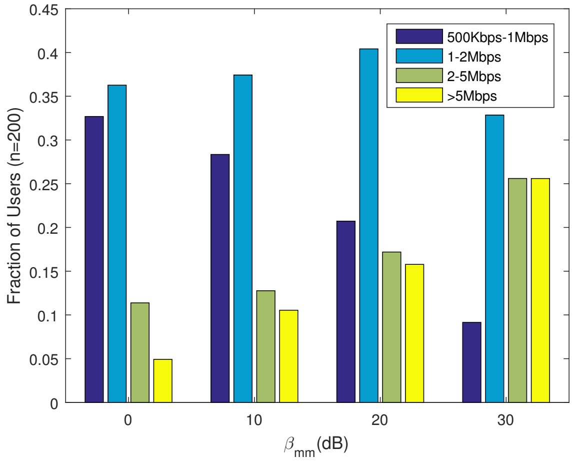


Figure 6: Rate trends for users with different bias factor ($n = 200$, $N = 20$, $N_U = 10$, $N_{mm} = 10$)

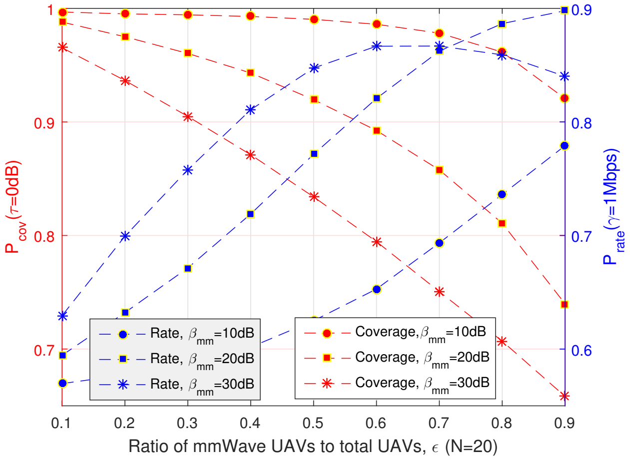


Figure 7: SNR and rate coverage trends for different bias factor ($\tau = 0dB, \gamma = 1Mbps, N = 20, n = 200$)

Sub-6GHz and mmWave bring contrasting characteristics to the HetNet. To gain valuable insight into the under study HetNet, in Fig. 7, we compare the coverage and rate trends with different biasing values, β_{mm}, and ratios 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 $\epsilon = 0.3$, the SNR coverage corresponds to 0.99, 0.95 and 0.9 for mmWave biasing values of 10dB, 20dB, and 30dB, respectively. Keeping the same ratio of mmWave UAVs, $\epsilon = 0.3$, rate coverage at γ =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 the SNR coverage degrades as more users offloads towards mmWave UAVs or the ratio of mmWave UAVs to total UAVs in the network, ϵ, increases and vice versa. On the other side, the rate coverage of the network improves as we increase the ratio of mmWave UAVs in the network or bias more users towards the 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 then we dominate network with sub-6GHz frequencies, but if rate is the QoS metric then mmWave frequencies should play a major role in the network. From Fig. 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 distribution between users associated with sub-6GHz tier and mmWave tier to satisfy QoS metrics of coverage and data rates. We observe that at a 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 the network performance will degrade. However, if we use a bias factor value of 20dB then we get an increase in rate coverage as we keep on increasing the fraction of mmWave UAVs upto $\epsilon = 0.9$. 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 $\beta_{mm} = 20$dB, 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. 8. The SNR coverage is plotted along with the rate coverage at three different thresholds, $\gamma = 500$Kbps, 750Kbps and 1 Mbps. We consider that our QoS metrics are both coverage and rates, therefore to experience a slow decay in the 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 how we can efficiently design a HetNet depending upon the QoS metrics. If the QoS required is SNR coverage, then we increase the UAVs operating in sub-6GHz range, however if the QoS metric is user data rates, then we increase the number of UAVs operating at mmWave frequencies.

IV. CONCLUSION

To meet the QoS requirements of bandwidth hungry applications, integration of mmWave with aerial platforms is indispensable. However, due to the 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 the sub-6GHz UAVs will enhance the SNR coverage and the mmWave UAVs will enhance the network capacity in terms of data rates. However, adjustment of network configuration will be required to meet the specific QoS requirements in terms of rate and coverage. As a future addition to our work, the 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 the mobility of UAVs by using a cost function based placement method for UAVs.

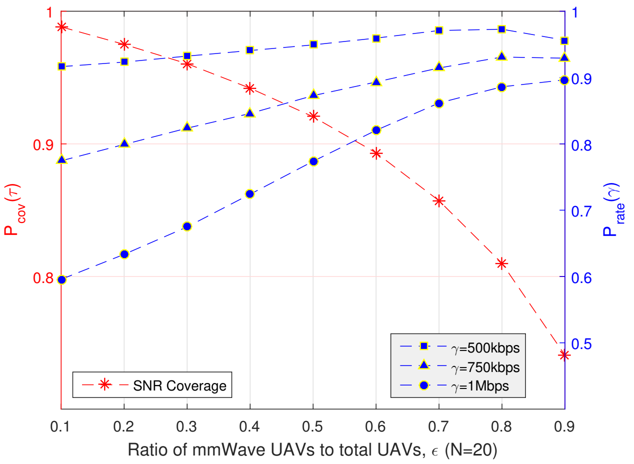


Figure 8: Variation in SNR and rate coverage and rate coverage $(N = 20,\ \beta_{mm} = 20dB, \tau = 0dB)$

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