Association of Small Cell Base Stations with UAVs in HetNets

By

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Approval

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Abstract

Small cell networks (SCNs) offer a cost-effective coverage solution to wireless applications demanding high data rates. However, in SCNs, a challenging problem is the proper management of backhaul links to small cell base stations (SCBSs). To make a good backhaul link, perfect line-of-sight (*LoS*) communication between the SCBSs and the core network plays a vital role. Traditionally, the traffic of SCBSs is routed to ground core network via fiber optics. However, the deployment cost and time is a huge concern when the number of SCBSs increases. Therefore, in this thesis, we use the scalable idea of employing unmanned aerial vehicles (UAVs) to provide connectivity between SCBSs and the core network. In particular, we focus on the association of SCBSs with UAVs by considering multiple communication-related factors including data rate limit and available bandwidth resources of the backhaul. Specifically, we address the optimum placement of UAVs to serve a maximum number of SCBSs while considering available resources using the unsupervised k-means algorithm. Afterward, we provide a two layer-based algorithm to maximize the sum rate and energy efficiency of the overall network while associating the SCBSs with UAVs. Simulation results show that the proposed methods outperform the conventional approach used in literature in terms of associated SCBSs, bandwidth consumption, available link utilization, sum rate, and energy efficiency maximization.

Dedication

I dedicate this thesis to my parents, my brother, and my sisters.

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.

I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

Author Name: **Muhammad Karam Shehzad**

Signature: ________________

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Chapter 1

Introduction

This chapter gives a brief introduction about the fifth-generation (5G) communication and the role of using unmanned aerial vehicles (UAVs) in 5G and beyond networks. Later on, thesis contribution is discussed, then the thesis organization concludes this chapter.

1.1 5G Technologies

The future of mobile communication is extended way beyond connecting people, in fact, it's about connecting everything [1–3]. Therefore, current 4G networks will move into 5G technology which will jump forward into a new era of wireless communication [4], [5]. The rapidly growing number of cellular users and their increasing demand for higher data rates mandates novel advancements in cellular technologies [6], [7]. To this end, the 5G and beyond 5G systems are looking into different solutions to meet the arising capacity and coverage demands [8–10]. Heterogeneous networks (HetNets) as shown in Fig. 1.1 have already been

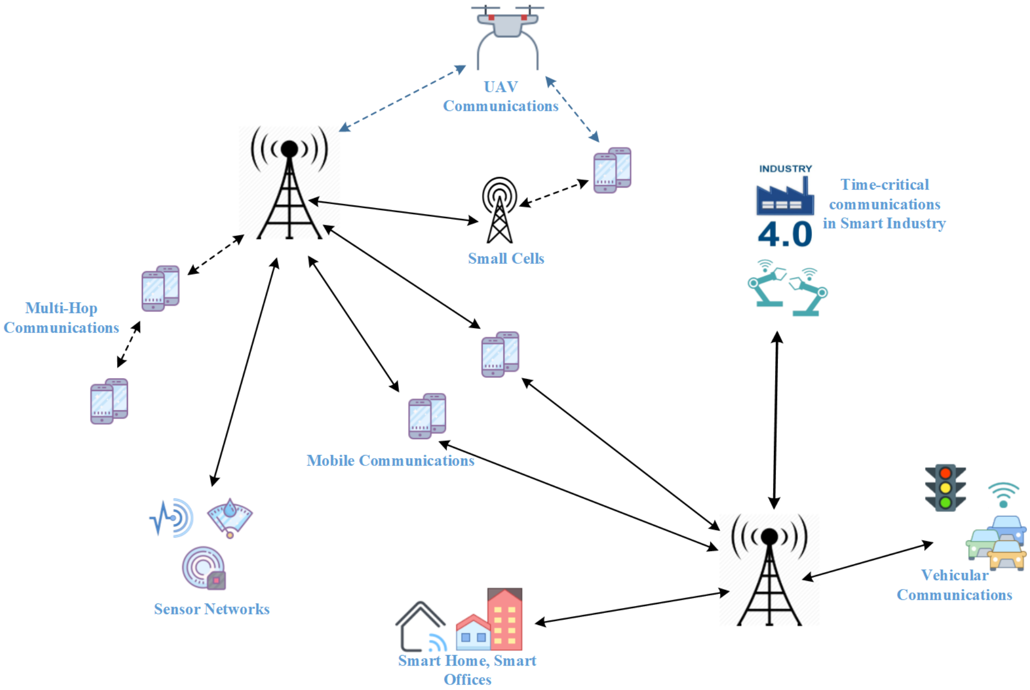

Figure 1.1: 5G Wireless Heterogeneous Network.

proposed in the 3rd Generation Partnership Project (3GPP) keeping in view the spectrum crunch and coverage issues [11], [12].

1.2 UAVs and 5G Networks

Within a short span of time, UAVs communication emerged as new paradigm shifts because of their instant deployment, flexible to change position and high probability of line-of-sight (*LoS*); thus improving the coverage and rate performance [13], [14]. Owing to the drastic increase of UAVs technology, this thesis attempts to use UAVs as aerial hubs for the connectivity between the core network and small cell base stations (SCBSs) in 5G HetNets. In particular, we address the association of SCBSs with the UAVs by considering the multiple communication-related factors including backhaul data rate limit, bandwidth resource available to each UAV, number of requests that each UAV can accommodate, and the maximum power with which a UAV can transmit a communication signal.

1.3 Thesis Contribution

The major contribution of this thesis work is given below:

- In this thesis, we find the optimum location of UAVs for the association of SCBSs. The proposed approach considers the optimal placement of UAVs to serve the maximum number of SCBSs and to maximize the sum rate of the overall network by keeping in view the constraints of backhaul data rate, available bandwidth, and some requests that each UAV can accommodate. In particular, given the distribution of SCBSs in dense HetNets, the optimum position is found by using the unsupervised k-means algorithm for the placement of UAV to maximize the sum rate of the entire network.
- Further, we extend the work to maximize the sum rate along with the energy efficiency of the overall network for the association of SCBSs with UAVs. Thus, we jointly optimize the energy efficiency and sum rate of the network. The proposed approach uses a two-layer model to achieve such kind of objective.

1.4 Thesis Organization

The remainder of this thesis is organized as follows: In Chapter 2, we give the background of UAVs and literature review related to the association of SCBSs with UAVs. Chapter 3 addresses the problem formulation and optimum placement of UAV using unsupervised learning. Chapter 4 focuses on the joint optimization of energy efficiency and sum rate which is the extension of Chapter 3. Finally, Chapter 5 concludes the thesis and gives some future directions.

Chapter 2

Background and Literature Review

This chapter delivers the background and literature review of unmanned aerial vehicles (UAVs) communications. Also, it discusses the small cell networks (SCNs) and their communication with the core network. Additionally, it focuses on the idea of using UAVs in traditional backhaul networks. Furthermore, the literature review related to the association of small cell base stations (SCBSs) with UAVs is addressed in detail.

2.1 UAVs Communication

Unmanned aerial vehicles (UAVs), commonly known as drones, network flying platforms (NFPs), balloons, evolution is a key approach to use as aerial networks because of their high coverage, promising rates, and flexible installation [15–20]. Owing to their flexible deployment, UAVs are the enablers of various applications including telecommunications, delivering supplies, rescue operations, surveillance, and monitoring [21–25]. Google's Project Wing [26] initiative is one

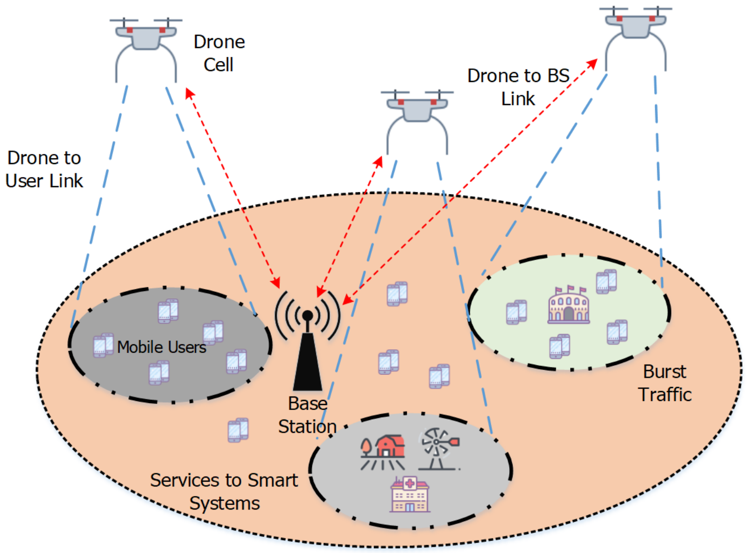

Figure 2.1: UAV Communication with Terrestrial Nodes.

of the prime examples of UAVs deployment and its broad applications. Despite the several advantages of UAVs, there are many technical challenges associated with UAVs communication which are addressed by a few researchers [27–32]. However, there are always some research gaps which are needed to be filled. For example, optimal 3D placement of UAVs, path planning, channel modeling, onbard energy of UAVs, the association of users with UAVs, handover and interference management are the key challenges [33–37].

2.1.1 Classification of UAVs

Depending on the application, UAVs are deployed accordingly based on their available power, quality-of-service (QoS) requirement, federal regulations, and nature of environment [28]. Based on the altitude levels, UAVs are categorized into three major types based on their altitude from the ground surface; low altitude platforms (LAPs), medium-altitude platforms (MAPs) and high altitude platforms

(HAPs) having a maximum height less than 5 km, between 5-10 km and greater than 10 km, respectively.

2.1.2 UAVs Regulations

UAVs regulations are one of the important limiting factors of UAVs deployment for various public and private applications [38]. On the one hand, there are many applications of UAVs, while, on the other hand, there are many concerns such as data protection, security, public safety and many more. These regulations vary based on different countries. For instance, in the United States of America (USA), UAV regulatory operations are issued by national aeronautics and space administration (NASA) and federal aviation authority (FAA) [39]. Interestingly, NASA is planning to develop UAVs regulations and their deployment in collaboration with FAA and federal communication commission (FCC).

2.1.3 UAVs Applications

There are several applications of UAVs, for example, in public safety networks, military operations, communication with people in disaster-struck regions in case of Tsunami, earthquake, etc. Also, UAVs can be used as aerial base stations (ABSs) in 5G cellular networks for coverage and capacity enhancement, 3D MIMO and millimeter wave (mmWave) communication, information dissemination in terrestrial networks, internet-of-things (IoTs) networks for data collections or communication, cache-enabled UAVs, cellular-connected drones as user equipments (UEs), flying ad-hoc networks, smart cities, and more importantly UAVs usage in backhaul networks which is the major focus of this thesis [40–42].

2.2 Small Cell Networks

Small-cell-networks (SCNs) are the promising solution to meet the ever-growing demands of cellular users [43–46]. However, in SCNs, a challenging problem is the proper management of backhaul links to small cell base stations (SCBSs) [47], [48]. To make a good backhaul link, perfect line-of-sight (*LoS*) communication between the SCBSs and the core network plays a vital role.

The traditional methods to route the traffic between SCBSs and core network include wired communication (e.g., fiber optics) or wireless microwave/millimeter-wave (mmWave) technology [14], [49]. Wireless communication links are further divided into line-of-sight (*LoS*) and non line-of-sight (*NLoS*) communication paths. *LoS* communication path is served using the free space optic (FSO) or mmWave technology but their short communication range is a major problem. Whereas, *NLoS* communication links have no coverage problems but suffer from high path-loss, low data rate, and high transmission power demands.

2.2.1 SCNs and UAVs Communication

Recently, the idea of using UAVs or NFPs, or drones as aerial hubs is introduced to route the traffic over backhaul links [50]. Keeping in view the power, bandwidth, and deployment cost constraints, UAVs is an appealing technique to provide *LoS* communication links between transmitters and receivers [51]. Hence, the traditional terrestrial backhaul network can be replaced by UAVs to provide a better communication link between the backhaul and SCBSs.

2.3 Challenges associated with UAV-enabled Networks

There are many technical challenges associated with UAV communication such as the association of SCBSs with UAVs, path planning, hover time maximization, and their placement according to their available energy levels [27,28,35,36]. Even though SCBSs' deployment is a promising approach to meet the higher data rate demand of cellular users in dense HetNets, the densification of SCBSs and their connectivity with the core network, known as fronthaul/backhaul network remains a key issue. Therefore, in this work, we investigate the optimum position of UAVs to route the downlink traffic of cellular users between the SCBSs and the core network. Specifically, the association problem of SCBSs with the UAV-hubs is addressed.

2.4 Association of Users with UAVs

In a very short period, the popularity of UAVs has grown to an irresistible level, and the communication techniques between UAVs and the ground nodes are addressed by many researchers. In [52], an air-to-ground (ATG) model for the communication between the UAVs and ground small cells is presented. Afterward, by considering the fixed path-loss between the UAV and ground node, a mathematical expression was derived by the same authors to estimate the maximum geographical area covered by a UAV [53]. Finally, in [54], considering the height and distance between the two UAVs, the geographical area covered by them is optimized.

Considering the scope of our work, in particular, the association of UAVs with ground users and their optimum placement is studied by a few researchers [55–63]. First of all, the association of UAV with ground nodes was addressed by [55], by considering only one UAV with signal-to-noise-ratio (SNR) as a quality-of-service (QoS) measure. Later on, the association problem was resolved by [56], considering multiple constraints such as backhaul data rate, available bandwidth to a UAV, and maximum path-loss for the case of single UAV as an aerial base station (BS). However, both the works presented in [55] and [56], solve the association problem using exhaustive search algorithms, which are computationally complex and therefore, impractical. Afterward, the aforementioned problem was addressed in [57] by using multiple UAVs as aerial BSs depending on the requirements of ground users and their available resources. In [57], the users are associated based on the best-received signal-to-interference-plus-noise-ratio (SINR), and then UAVs are placed to solve the optimization problem using the practical swarm optimization (PSO) algorithm. However, the downside of PSO is a low convergence rate at high computation cost in the iterative process.

In [60], by distributing the ground users, UAVs, and terrestrial BSs, optimal transport theory is adopted to associate the ground users. The objective was to obtain delay optimal cell association. Finally, in [61–63], the association of SCBSs with UAVs was addressed by considering the backhaul data rate, available bandwidth to a UAV, and the number of links as association constraints. In the first attempt, SCBSs are distributed using *Matern type-I* hardcore process and then UAVs are computed based on the available link constraint and then distributed using the same process. The priority was given to the SCBSs demanding maximum data rate [61], minimum data rate plus bandwidth [62], and higher spectral efficiency [63]. However, in [61–63], less number of SCBSs are served by UAVs.

Also, the available resources are not efficiently utilized.

Chapter 3

Unsupervised Learning-based UAVs Placement

In this chapter [1], we find the optimum location of UAVs for the association problem discussed in [61–63]. The proposed approach considers the optimal placement of UAVs to serve the maximum number of SCBSs by keeping in view the constraints of backhaul data rate, available bandwidth, and a number of requests that each UAV can accommodate. In particular, given the distribution of SCBSs in dense HetNets, the optimum position is found by using the unsupervised k-means algorithm for the placement of UAV. The results show that the proposed approach results in serving the maximum number of SCBSs for all types of demands (either serving maximum, minimum or spectral efficient data rates). Simulation results also show that the proposed unsupervised learning-based UAVs placement outperforms in terms of maximizing sum rate, link utilization, minimum bandwidth consumption, and sending a minimum number of SCBSs in outage.

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[1] This Chapter has been accepted as a conference paper [64] in 89th IEEE VTC held in Malaysia in May 2019 and is publicly available at [65]

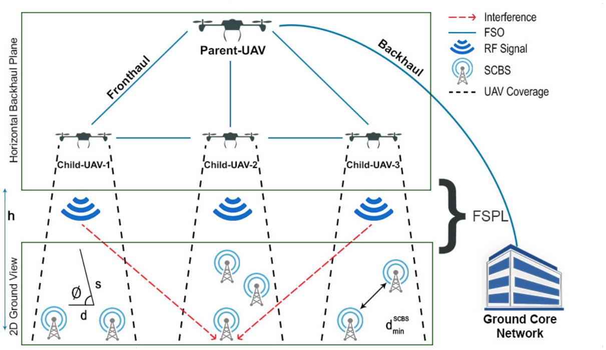

Figure 3.1: Pictorial View of Association Problem.

The chapter is organized as follows. In Section 3.1, we present the system model, in Section 3.2 problem formulation is addressed, Section 3.3 delivers objective, Section 3.4 focuses on proposed approach. Finally, Section 3.5 presents the results and their discussions.

3.1 System Model

Consider a HetNet shown in Fig. 3.1 where the association problem for various network entities is shown. There are three major parts of the HetNet namely SCBSs, UAVs, and a ground core network gateway. Let $\mathcal{N}$ and $\mathcal{M}$ be the set of all SCBSs and UAVs, respectively and let $\mathcal{M}_0$ be the singleton set representing the parent-UAV. Further, we assume that the total number of elements of sets $\mathcal{N}$ and $\mathcal{M}$ are denoted by N and M, respectively. Thus, N SCBSs are communicating with the M UAVs, where the height of a UAV from a ground SCBS is represented as h. We assume that all the M UAVs can share control information including SINR of each UAV to SCBSs, demanded data rate and required bandwidth of each SCBS, with one another. The parent-UAV is placed slightly at a higher height such that perfect *LoS* communication is possible from the M UAVs. In the considered model, we call the M UAVs as child-UAVs. Also, all the M UAVs directly share their information with the parent-UAV through FSO links. Moreover, parent-UAV is connected with the ground core network through another FSO link. In the above scenario, we assume that the system model does not change for the time of operation and N SCBSs are active in this period. Next, we present the path-loss model for communication between N SCBSs and M UAVs. Then, later on, we formulate the problem.

3.1.1 Path Loss Model

For the communication between the UAVs and SCBSs, ATG path-loss model is adopted. The ATG model is divided into two states, that is, *LoS* and *NLoS* communication links. In *LoS* scenario, the probability of *LoS*, $\mathbb{P}_{\text{LoS}}$ is an important factor and it is dependent on the height, location, angle, and obstacles between a UAV and a ground node, and is given in [52] and [53] as

$$\mathbb{P}_{\text{LoS}} = \Big[1+\alpha \exp\big\{-\beta(\phi-\alpha)\big\}\Big]^{-1}. \tag{3.1}$$

Also, $\mathbb{P}_{\text{NLoS}} = 1-\mathbb{P}_{\text{LoS}}$. The parameter α and β in (3.1) are constants and solely depend on the operational environment, and ϕ is the angle (in degrees) between an SCBS and a UAV given by $\phi = \tan^{-1}\left(\frac{h_j}{d_i^j}\right)$, where d_i^j denotes the horizontal Euclidean distance between the j^{th} UAV and i^{th} SCBS and h_j is the height of the UAV. The symmetry is assumed for all UAVs, which implies that they are at the same height. The position of UAVs and the SCBSs in a Cartesian coordinate system is denoted as (x_j, y_j, h_j), and (x_i, y_i), respectively.

The total path-loss (expressed in dB) including fading attenuation F between the UAV and an SCBS is given as

$$\Lambda = K_0 + \mathbb{P}_{\text{LoS}} \cdot \mu_{\text{LoS}} + \mathbb{P}_{\text{NLoS}} \cdot \mu_{\text{NLoS}} - F \qquad , \tag{3.2}$$

where $K_0 = 10\log_{10}\left(\frac{4\pi s f_c}{c}\right)^{\gamma}$, which is the free-space-path-loss (FSPL), f_c is the carrier frequency, c is the speed of light, γ is the path-loss exponent, and $s = \sqrt{d^2 + h^2}$. In addition, μ_{LoS} and μ_{NLoS} are the attenuation factors for the *LoS* and *NLoS* communication links, respectively. Also,

$$F(dB) = \mathbb{P}_{\text{LoS}} \cdot h_0 + \mathbb{P}_{\text{NLoS}} \cdot h_1 \qquad . \tag{3.3}$$

The envelopes of h_0 and h_1 are *Nakagami* distributed, that is, $|h_p| \sim Nakagami(m)$ where $p = \{0, 1\}$, and m is the shape parameter which takes the value 1 for Rayleigh fading and any value for h_0 depending on the environment. Hence, the received power at i^{th} SCBS from j^{th} UAV is, written as $\Omega^j_{r_i}(dB) = \Omega^j_t - \Lambda$, where Ω^j_t is the total transmitted power of j^{th} UAV. The SINR received by the i^{th} SCBS from j^{th} UAV is expressed as

$$\Gamma^j_i = \frac{\Omega^j_{r_i}}{\sum_{v=1, v \neq j}^{M} \Omega^v_{r_i} + \sigma_n^2} \qquad , \tag{3.4}$$

where σ_n^2 is the noise power.

3.2 Problem Formulation

Consider a downlink scenario in which N SCBSs are downloading the data from the ground core network via M UAVs. We assume that the SCBSs are distributed using *Matern type-I* hard core process [66] with density of ρ per square meter, having a minimum separation of $d_{\min}^{SCBS}$ between them. This formulation results in random distribution of SCBSs in Cartesian coordinates. We need to find the required number of UAVs such that all the SCBSs can be served. For this purpose, suppose that each UAV can accommodate up to maximum of L requests from a total of N SCBSs. Therefore, M can be obtained by

$$M = \left\lceil \frac{N}{L} \right\rceil \qquad ,$$

where $\lceil . \rceil$ denotes the ceil operator. Let $\mathbf{A}$ be an association matrix, in which, row and column represent the entry of SCBSs and UAVs, respectively. Let $a_{ij} \in \{0,1\}$ denotes the entries of matrix $\mathbf{A}$. In case of connectivity, $a_{ij} = 1$, otherwise $a_{ij} = 0$. Suppose the demanded data rate of i^{th} SCBS from j^{th} UAV is denoted by r_i^j and therefore, the required bandwidth can be calculated as,

$$w_i^j = r_i^j / \log_2 (1 + \Gamma_i^j) \qquad . \tag{3.5}$$

3.3 Objective

The objective is to find the optimum location of UAV with a predefined optimum number of UAVs such that total data rate of the overall system can be maximized. Therefore, the optimization problem (heuristic in nature) becomes,

$$\max_{\{a_{ij}\}} \sum_{i=1}^{N} \sum_{j=1}^{M} r_i^j \cdot a_{ij} \tag{3.6a}$$

s.t.

$$\sum_{i=1}^{N}\sum_{j=1}^{M} r_i^j \cdot a_{ij} \leq R_B, \tag{3.6b}$$

$$\sum_{i=1}^{N} w_i^j \cdot a_{ij} \leq W_j, \qquad \forall_j \tag{3.6c}$$

$$\sum_{i=1}^{N} a_{ij} \leq L_j, \qquad \forall_j \tag{3.6d}$$

$$\Gamma_i^j \cdot a_{ij} \geq \Gamma_{\min}, \qquad \forall_{i,j} \tag{3.6e}$$

$$\sum_{j=1}^{M} a_{ij} = \{0 \, \text{or} \, 1\}, \qquad \forall_i \tag{3.6f}$$

It can be seen from (3.6) that the association of SCBSs with UAVs is limited by a number of factors including backhaul data rate R_B, bandwidth available to each UAV W, maximum number of requests that can be accommodated by each UAV L, and minimum SINR $\Gamma_{\min}$ criteria to satisfy the QoS requirements. Lastly, each SCBS is only connected with one UAV.

3.4 Solution

The solution of the objective function in (3.6) is obtained using the k-means clustering algorithm [67]. The aim is to split the N SCBSs into k regions on the basis of Euclidean distance. Therefore, the k-means algorithm tries to minimize the distance within the cluster nodes by performing iterations.

Suppose, $\mathcal{N} = \{n_1, n_2, ..., n_N\}$ be a vector representing the N number of SCBSs, k-means partitions the vector $\mathcal{N}$ into k regions represented by $\mathfrak{R} = \{\mathfrak{R}_1, \mathfrak{R}_2, ..., \mathfrak{R}_k\}$ so as to minimize the variance within the region,

$$\boldsymbol{arg}\min_{\mathfrak{R}} \sum_{l=1}^{k} \sum_{\mathcal{N}\in\mathfrak{R}_l} \left\|\mathcal{N} - \mu_{\mathbf{l}}\right\|^2 \quad , \tag{3.7}$$

where $\mu_{\mathbf{l}}$ represents the centroids, which are the optimized positions of UAVs. The above expression minimizes the distance within the region and maximizes outside of the region. Therefore, we place the M UAVs on obtained points for the association problem. The algorithm [61–63] for the association problem is summarized in Algorithm 3.1.

3.5 Simulation Results

We consider the area of 16 km^2 in which SCBSs are distributed using *Matern type-I* with a density of ρ per square meter and having a minimum distance of $d_{\min}^{SCBS}$ between the neighbors. As a result, 28 SCBSs are retained from this process. Then M UAVs are placed using (3.7). Now, we assign the data rates randomly from the vector $\mathbf{r}_{SCBS}$ and obtain the results using the algorithm presented in Algorithm 3.1. The parameters for simulation are listed in Table. 3.1. The results are simulated for three different scenarios.

1. Scenario 1: the priority is given to SCBSs demanding maximum data rate.
2. Scenario 2: we give the priority to those, demanding minimum data rate plus bandwidth.
3. Scenario 3: the priority is given to SCBSs with the highest spectral efficiency.

In the considered scenarios, the outcome of Algorithm 3.1 is investigated for

Algorithm 3.1 Association of SCBSs with UAVs

```
Input: $N, M, L, W, R_B, \Gamma_i^j, r_i^j, w_i^j$
Output: $\mathbf{A}$
Initialize: $\mathbf{A} = \emptyset$
for $i = 1$ to $N$ do
    Make a list of UAVs that satisfy $\Gamma_{\text{min}}$ criterion
end
for $j = 1$ to $M$ do
    if Scenario 1 then
        Select SCBS having max. data rate
    end
    else if Scenario 2 then
        Select SCBS having $\mathbf{min}(r_i^j + w_i^j)$
    end
    else
        Select SCBS having higher spectral efficiency
    end
    Initialize counters: $T_L = 0$, $T_B = 0$
      while $T_L < L \wedge T_B < W$ do
        if $T_B + w_i^j \leq W$ then
            Update $\mathbf{A}_{ij} = 1$, $T_L = T_L - 1$ and $T_B = T_B + w_i^j$
        end
    end
end
Initialize: $T_r$ as total data rate of associated SCBSs
while $T_r > R_B$ do
    Select UAV with min. associated links  if Scenario 1 or Scenario 3 then
        Select SCBS with min. data rate
    end
    else
        Select SCBS with $\mathbf{max}(r_i^j + w_i^j)$
    end
    De-associate the selected pair and update $\mathbf{A}_{ij} = 0$,
      $T_L = T_L - 1$, $T_r = T_r - r_i^j$ and $T_B = T_B - w_i^j$
end
```

Table 3.1: Simulation Parameters

Parameter	**Value**	**Parameter**	**Value**
f_c	2 GHz	Γ_{min}	-5 dB
β	0.16	σ_n	-125 dB
α	9.61	μ_{LoS}	1 dB
μ_{NLoS}	20 dB	h	300 m
ρ	$2 \times 10^{-6}/\ \text{m}^2$	$d_{\text{min}}^{\text{SCBS}}$	250 m
Area	16 km^2	γ	2
$\mathbf{r}_{\text{SCBS}}$	$\{20, 40, 60, 80, 100\}$ Mbps		

Table 3.2: Comparison of Results with constraints $R_B = 1.4$ Gbps, $\Omega_t = 1.3$ W, and $W = 200$ MHz averaged over 100000 iterations.

Evaluation Parameters	**Conventional Approach**			**Proposed Approach**		
	S-1	**S-2**	**S-3**	**S-1**	**S-2**	**S-3**
Total Associated SCBSs	17	20	16	21	23	21
Avg. BW Consumption (MHz)	181.21	161.13	183.53	162.43	153.44	165.61
sum rate (Gbps)	1.08	1.01	1.04	1.36	1.24	1.34
SCBSs in Outage	11	8	12	7	5	7
Avg. Link Utilization (%)	60.71	71.42	57.14	75	82.14	75

both the approaches (i.e., conventional [61–63] and proposed).

Table. 3.2 illustrates the performance in terms of associated SCBSs, average bandwidth consumption, sum rate of overall system, and average link utilization of all four UAVs, for conventional and the proposed approach. Overall, the proposed approach associated the highest number of SCBSs in all scenarios, and conventional approach accommodated lowest. In addition, proposed approach consumed less bandwidth to reach the objective criterion of sum rate. Moreover, less number of SCBSs experience outage, and the percentage of link utilization is maximum as compared to the conventional approach. In Scenario 1 and 3, both approaches associated less SCBss as compared to Scenario 2 because the priority was given to higher data rate clients. Similarly, in Scenario 2 of the proposed approach,

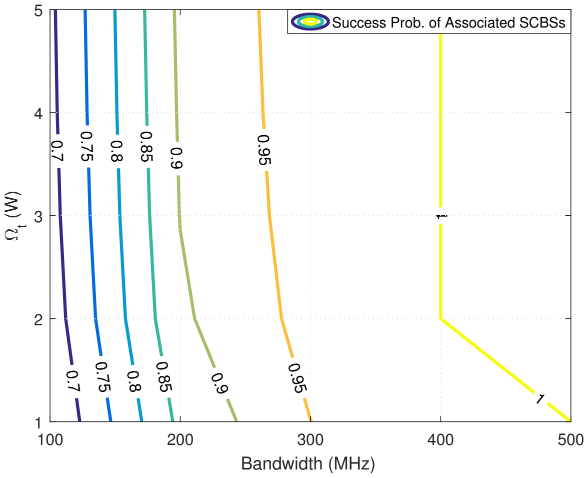

Figure 3.2: The contour plot of the success probability of associated SCBSs against Ω_t and W for the proposed approach with constraints $R_B = 1.7$ Gbps, and $L = 11$ averaged over 1000 iterations. (Scenario 2)

more requests are served due to the priority of minimum data rate demands. On the other hand, the conventional approach results in serving fewer requests, more bandwidth usage, less link utilization, and more outage of SCBSs. Also, the conventional approach does not achieve objective criteria due to higher bandwidth requirements by each UAV. In Table 3.2, it can also be observed that the proposed approach still needs fewer associations to achieve the objective, therefore, we need to find exact bandwidth requirement and transmitted power to do that, which we deal in the next figure.

Fig. 3.2 depicts the success probability of association for different combinations of transmitted power and required bandwidth. It can be noticed from the figure that the increase in transmission power does not increase the number of associations. In contrast, the increase in bandwidth increases the success probability of association. It can be seen that 100% success probability is achieved at 1.5 W of transmission power and at 475 MHz bandwidth consumption.

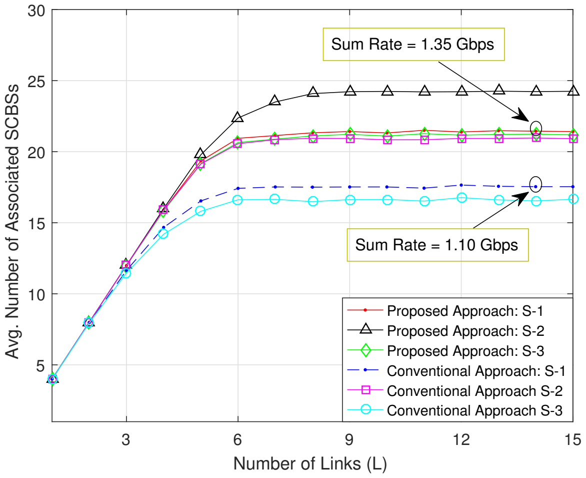

Figure 3.3: Number of Links vs. Average Associated SCBSs with constraints $R_B = 1.4$ Gbps, $\Omega_t = 1.3$ W, and $W = 200$ MHz averaged over 1000 iterations for all scenarios.

Finally, Fig. 3.3 reveals the performance of both approaches for all scenarios when the number of links are increased from 1 to 15. It can be concluded that the increase in the number of links leads to more SCBSs' associations for both approaches. However, the proposed approach outperforms the conventional one. For example, for $L = 14$, Scenario 1 of proposed approach associates 22 SCBSs whereas conventional approach associates 17, for the same scenario. Also, sum rate is maximized for the proposed approach as compared to the conventional approach. Moreover, it can be observed that scenario 2 has served more requests in both approaches because of minimum data rate demands.

In summary, it can be deduced from the above results that proposed approach associates more SCBSs by consuming less bandwidth. In 5G+ networks, available bandwidth resources will be limited and hence, by keeping in view the bandwidth usage, our approach gives best results.

Chapter 4

Joint Optimization of Energy Efficiency and Sum Rate

In this chapter, we present the optimum placement of unmanned aerial vehicles (UAVs) to solve the association of small cell base stations (SBs) with UAVs by keeping in view the objective criteria of maximizing sum rate and energy efficiency of the overall network. Also, the communication related constraints, i.e., backhaul data rate limit, bandwidth available to each UAV, number of requests that each UAV can accommodate, and the maximum power at which each UAV can transmit the communication signal. The solution of this problem is obtained using a two layer framework, in the first layer, UAVs are placed using unsupervised k-means algorithm. And the second layer performs the iterative algorithm to maximize the sum rate and energy efficiency of overall network, which is the objective of this work. The performance of the proposed approach is compared with work presented in literature.

This chapter is organized as follows: In Section 4.1, system model is pre-

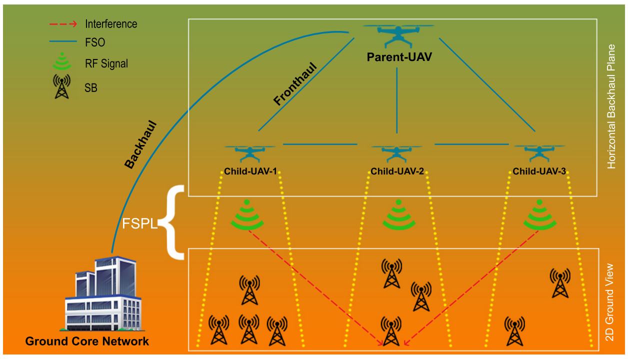

Figure 4.1: Graphical representation of Association problem.

sented, in Section 4.2 problem formulation is addressed. Proposed approach is described in Section 4.3. Section 4.4 gives results and their analysis.

4.1 System Model

Consider a UAV-enabled wireless HetNet, as shown in Fig. 4.1, in which C child-UAVs are hovering at some height H from the ground level to serve U ground small cell base stations (SBs), and the C child-UAVs are connected with a parent-UAV P via free space optics (FSO) link. In addition, we assume that C child-UAVs can share the control information (including signal-to-interference-plus-noise ratio (SINR) of each child-UAV to SB, bandwidth and data rate requirement of each SB) with each other via another FSO link[1]. However, each child-UAV will directly send the collected information from its associated SBs to the parent-UAV. Further, parent-UAV P is placed at a higher height than child-UAVs such that perfect line-of-sight (LoS) communication between parent and child-UAVs could be possible and parent-UAV is connected through a single hop FSO link with ground

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[1] Here we assume that communication link between each child-UAV is ideal which means no losses, bandwidth or data rate requirements are considered. However, they can be affected by weather conditions [50], we leave this as future work.

core-network located at some location $\mathbf{G}_0 = (x_0, y_0)$. Moreover, it is assumed that system model does not change for a time interval $[0, T]$ and active SBs are taken into account during this time of operation. For the sake of notational convenience, we denote the sets of child-UAVs and ground SBs as $\mathcal{C} \triangleq \{1, ..., C\}$ and $\mathcal{S} \triangleq \{1, ..., S\}$, respectively. Additionally, we represent parent-UAV with singleton set $\mathcal{P}_0$. We consider the 3D Cartesian coordinate system, where each child-UAV $\mathsf{c} \in \mathcal{C}$ has horizontal coordinate $\mathbf{u}_c = (s_c, t_c)$ and height H. We represent the horizontal coordinate of SB $\mathsf{s} \in \mathcal{S}$ as $\mathbf{v}_s = (x_s, y_s)$, with altitude zero. In the considered case, the distance from child-UAV c to SB s is denoted as

$$d_{\mathsf{c,s}} = \sqrt{H^2 + \|(\mathbf{u}_c - \mathbf{v}_s)\|^2}, \quad \mathsf{c} \in \mathcal{C}, \mathsf{s} \in \mathcal{S} \qquad . \tag{4.1}$$

Further, probability of *LoS* plays a vital role in UAV-assisted wireless network and is presented in [52] and [53] as

$$\mathsf{P}_{\text{LoS}} = \frac{1}{1 + a \cdot \exp\left\{ -b(\varphi - a) \right\}} \qquad , \tag{4.2}$$

Here the parameter a and b are constants and their values depends upon the operational environment, and φ is the angle (in degrees) between child-UAV c and SB s. It is important to note that $\mathsf{P}_{\text{NLoS}} = 1 - \mathsf{P}_{\text{LoS}}$.

4.1.1 Path Loss Model

We consider the wireless channel between child-UAVs and SBs, therefore, we use the air-to-ground (ATG) path-loss model presented in [52] and [53]. The total path-loss (expressed in dB) between child-UAV c and SB s is given as

$$\Psi_{\mathsf{c},\mathsf{s}} = F_0 + \mathsf{P}_{\mathrm{LoS}} \cdot \zeta_{\mathrm{LoS}} + \mathsf{P}_{\mathrm{NLoS}} \cdot \zeta_{\mathrm{NLoS}}, \quad \mathsf{c} \in \mathcal{C}, \mathsf{s} \in \mathcal{S} \quad , \tag{4.3}$$

where $F_0 = 20\log_{10}\left(\frac{4\pi \cdot d_{\mathsf{c},\mathsf{s}}}{\lambda}\right)$, which is the free-space-path-loss (FSPL), ζ_{LoS} and ζ_{NLoS} are the attenuation factors for the *LoS* and *NLoS* links, respectively.

The signal-to-interference-plus-noise ratio (ψ) of the $\mathsf{c}-th$ child-UAV at the $\mathsf{s}-th$ SB is written as

$$\psi_{\mathsf{s},\mathsf{c}} = \frac{\mu}{\sigma_n^2 + I_r}, \qquad \mathsf{s} \in \mathcal{S}, \mathsf{c} \in \mathcal{C} \qquad , \tag{4.4}$$

where μ is the received power at $\mathsf{s}-th$ SB from $\mathsf{c}-th$ child-UAV, I_r represents the sum of the interference from other child-UAVs, and σ_n^2 is the noise power.

4.2 Problem Formulation

First of all, we distribute small cell bases stations (SBs) using *Matern type-I* hard-core process [66] with success probability of ς per square meter and having a minimum separation of $d_{\min}$ from each other. As a outcome, U SBs are obtained and we assign random data rate demands (r) to these SBs. Now we find the total number of child-UAVs C to serve the U ground SBs, and for this purpose we consider that each child-UAV can make up to L number of links. Therefore, total child-UAVs C can be calculated as

$$C = \left\lceil \frac{U}{L} \right\rceil \qquad ,$$

where $\lceil . \rceil$ denotes the ceil operator.

Consider the downlink scenario of the network in which U SBs are downloading the data from core network via C child-UAVs. Therefore, the bandwidth requirement of each SB $\mathsf{s} \in \mathcal{S}$ from $\mathsf{c} \in \mathcal{C}$ is written as

$$w_{\mathsf{s},\mathsf{c}} = r_{\mathsf{s},\mathsf{c}} / \log_2 \left(1 + \psi_{\mathsf{s},\mathsf{c}}\right), \qquad \mathsf{s} \in \mathcal{S}, \mathsf{c} \in \mathcal{C} \qquad , \tag{4.5}$$

where $r_{\mathsf{s},\mathsf{c}}$ is the demanded data rate of $\mathsf{s}-th$ SB from $\mathsf{c}-th$ child-UAV. Since, data rate demands are distributed randomly from predefined data rate vector $\mathbf{r}_{SB}$. So, each SB $\mathsf{s} \in \mathcal{S}$ demands the same data rate from all child-UAVs, i.e., $r_{\mathsf{s},\mathsf{c}} = r_{\mathsf{s}}$, $\forall \mathsf{c} \in \mathcal{C}$.

Next, we assume that communication between U ground SBs and C child-UAVs is limited by a number of communication related parameters i.e., maximum power P_{c}^{max} that each child-UAV $\mathsf{c} \in \mathcal{C}$ can transmit to improve energy efficiency η_{EE}. Secondly, total backhaul data rate R_B, which is the limit of total rate that can be supported by the link[2] between parent-UAV $\mathcal{P}_0$ and ground core-network. Thirdly, maximum bandwidth W_{c} limit that each child-UAV $\mathsf{c} \in \mathcal{C}$ can distribute. Fourthly, each child-UAV $\mathsf{c} \in \mathcal{C}$ can accommodate maximum of L requests. Fifthly, in order to maintain quality-of-service (QoS) requirements between child-UAVs and ground SBs, minimum SINR criterion should satisfy which plays a vital role as decrease in SINR values results in high path-loss. Lastly, each SB $\mathsf{s} \in \mathcal{S}$ will only be served by only one child-UAV $\mathsf{c} \in \mathcal{C}$.

Suppose $m \in \{0, 1\}$ denotes the connection between any ground SB $\mathsf{s} \in \mathcal{S}$ and child-UAV $\mathsf{c} \in \mathcal{C}$. In case of connectivity, $m = 1$, and zero otherwise. Further, let

---

[2] Here we also assume that there is strong *LoS* communication in this link. Therefore, this path is ideal and there are no losses.

M be the connectivity matrix, each row and column of matrix **M** represents the SB and child-UAV, respectively.

The transmission power of all the child-UAVs is limited to P^{max}. In addition, each link between the child-UAVs and SBs costs individual circuit power denoted by P_c. Thus the total transmitted power by child-UAVs is written as

$$P_T = \varepsilon \cdot \sum_{\mathsf{s}\in\mathcal{S}} \sum_{\mathsf{c}\in\mathcal{C}} p_{\mathsf{c},\mathsf{s}} \cdot m_{\mathsf{s},\mathsf{c}} + N \times P_c \qquad , \tag{4.6}$$

where N represents the total number of associated SBs, ε represents the inverse of power amplifier efficiency, $p_{\mathsf{c},\mathsf{s}}$ is transmit power of a child-UAV $\mathsf{c} \in \mathcal{C}$ to SB $\mathsf{s} \in \mathcal{S}$. Therefore, energy efficiency η_{EE}, in bits/s/Watt, is the amount of energy required by the system to transmit data and is expressed as

$$\eta_{EE} = \frac{\sum_{\mathsf{s}\in\mathcal{S}} \sum_{\mathsf{c}\in\mathcal{C}} r_{\mathsf{s},\mathsf{c}}}{\varepsilon \cdot \sum_{\mathsf{s}\in\mathcal{S}} \sum_{\mathsf{c}\in\mathcal{C}} p_{\mathsf{c},\mathsf{s}} \cdot m_{\mathsf{s},\mathsf{c}} + N \times P_c} \qquad . \tag{4.7}$$

The objective is to find the optimum location of UAV with a predefined optimum number of child-UAVs such that total sum rate of the overall system and energy efficiency η_{EE} can be maximized by keeping in view the communication constraints discussed above. Therefore, the joint optimization problem becomes

$$\max_{\{m_{\mathsf{s},\mathsf{c}},\ p_{\mathsf{c},\mathsf{s}}\}} \sum_{\mathsf{s}\in\mathcal{S}} \sum_{\mathsf{c}\in\mathcal{C}} \{r_{\mathsf{s},\mathsf{c}} \cdot m_{\mathsf{s},\mathsf{c}},\ \eta_{EE}\} \tag{4.8a}$$

subject to

$$\sum_{\mathsf{s}\in\mathcal{S}}\sum_{\mathsf{c}\in\mathcal{C}} r_{\mathsf{s,c}} \cdot m_{\mathsf{s,c}} \leq R_B, \tag{4.8b}$$

$$\sum_{\mathsf{s}\in\mathcal{S}} p_{\mathsf{c,s}} \leq P_{\mathsf{c}}^{max}, \qquad \forall \mathsf{c} \in \mathcal{C} \tag{4.8c}$$

$$\sum_{\mathsf{s}\in\mathcal{S}} w_{\mathsf{s,c}} \cdot m_{\mathsf{s,c}} \leq W_{\mathsf{c}}, \qquad \forall \mathsf{c} \in \mathcal{C} \tag{4.8d}$$

$$\sum_{\mathsf{s}\in\mathcal{S}} m_{\mathsf{s,c}} \leq L_{\mathsf{c}}, \qquad \forall \mathsf{c} \in \mathcal{C} \tag{4.8e}$$

$$\psi_{\mathsf{s,c}} \cdot m_{\mathsf{s,c}} \geq \psi_{\min}, \qquad \forall \mathsf{c} \in \mathcal{C}, \mathsf{s} \in \mathcal{S} \tag{4.8f}$$

$$\sum_{\mathsf{c}\in\mathcal{C}} m_{\mathsf{s,c}} = \{0 \,\mathrm{or}\, 1\}, \qquad \forall \mathsf{s} \in \mathcal{S} \tag{4.8g}$$

It can be seen from (4.8) that the association of SBs with child-UAVs is limited by a number of factors including backhaul data rate R_B for the link between parent-UAV and ground core-network, maximum transmit power P_c^{max} of a child-UAV, bandwidth available to each child-UAV W_{c}, maximum number of requests L that can be accommodated by each child-UAV, and minimum SINR $\psi_{\min}$ criteria to satisfy the QoS requirements. Lastly, each SB is only connected with one child-UAV.

4.3 Proposed Approach

The solution of the objective problem is divided into two layers. In the first layer, child-UAVs are placed using unsupervised learning k-means clustering algorithm [67], and in the second layer, iterative algorithm is performed to meet the objective criteria defined in (4.8). Thus, below we describe the two layers to find the optimal solution of the problem.

4.3.1 Initial UAVs Placement

The target is to split the U small cell base stations (SBs) into k regions on the basis of Euclidean distance. Therefore, the k-means algorithm tries to minimize the distance within the cluster nodes and maximizes outside of the cluster nodes by performing iterations.

Suppose, $\mathfrak{U} = \{u_1, u_2, ..., u_U\}$ be a vector representing the U number of SBs, k-means partitions the vector $\mathfrak{U}$ into k regions represented by $\boldsymbol{\mathfrak{R}} = \{\mathfrak{R}_1, \mathfrak{R}_2, ..., \mathfrak{R}_k\}$ so as to minimize the variance within the region and maximize outside of the region,

$$\boldsymbol{arg} \min_{\boldsymbol{\mathfrak{R}}} \sum_{i=1}^{k} \sum_{\mathfrak{U} \in \mathfrak{R}_i} \left|\left|\mathfrak{U} - \chi_{\mathbf{i}}\right|\right|^2 \qquad , \tag{4.9}$$

where $\chi_{\mathbf{i}}$ represents the centroids, which are the initial positions of child-UAVs. Therefore, we place the C child-UAVs on obtained points and perform the iterative algorithm described below. The algorithm for the association problem is summarized in Algorithm 4.1.

4.3.2 Iterative Algorithm

In the optimization process, child-UAVs change their vertical position V for each iterative step t simultaneously and perform the association using Algorithm 4.1. At the beginning, we assume that child-UAVs are hovering at height $H = 300m$ from the ground level, i.e., $V_1 = (\mathbf{u}_c, 300)$. The increase in the height H at $t+1$ is dependent on step length τ, and the vicinity is limited between $H = 300m$ to $H = 700m$. All the child-UAVs keep on increasing their height concurrently in the vicinity until the objective function described in (4.8) is not achieved.

Algorithm 4.1 Association of SBs with child-UAVs

```
Input: $\mathcal{S}$, $\mathcal{C}$, $L$, $W_c$, $R_B$, $\psi_{s,c}$, $r_{s,c}$, $w_{s,c}$
Output: $\mathbf{M}$
Initialize: $\mathbf{M} = \emptyset$
// Task at each SB
for $\mathcal{S}$ do
    Select child-UAV with $\psi_{\max}$
end
// Task at each child-UAV
for $\mathcal{C}$ do
    if Scenario 1 then
        Select SB having max. data rate max $(r_{s,c})$
    end
    else if Scenario 2 then
        Select SB having $\mathbf{min}(r_{s,c} + w_{s,c})$
    end
    else if Scenario 3 then
        Select SB having higher spectral efficiency
    end
    else
        Select SB having maximum $\psi_{s,c}$
    end
    Initialize counters: $T_L = 0$, $T_W = 0$
    while $T_L < L \wedge T_W < W_c$ do
        if $T_W + w_{s,c} \leq W_c$ then
            Update $\mathbf{M}_{s,c} = 1$, $T_L = T_L - 1$ and $T_W = T_W + w_{s,c}$
        end
    end
end
// Task at parent-UAV
Initialize: $T_R$ as total data rate of associated SBs
while $T_R > R_B$ do
    Select UAV with min. associated SBs
    if Scenario 1 or Scenario 3 or Scenario 4 then
        Select SB with min. data rate min $(r_{s,c})$
    end
    else
        Select SB with $\mathbf{max}(r_{s,c} + w_{s,c})$
    end
    De-associate the selected pair and update $\mathbf{M}_{s,c} = 0$,
      $T_L = T_L - 1$, $T_R = T_R - r$ and $T_W = T_W - w_{s,c}$
end
```

4.4 Simulation Results

The area of 16 km^2 is considered in which small cell base stations (SBs) are distributed using *Matern type-I* hard-core process [66] with success probability of ς per square meter and having a minimum separation of $d_{\min}$ in *meters* between their neighbors. As an outcome, 28 SBs are obtained and then data rates are assigned randomly from the vector $\mathbf{r}_{SB}$. Further, the maximum transmit power P_c^{max} of a UAV is limited to 1.3 W, the value of P_c is set to 0.1 W, and ε is 38%. Finally, C child-UAVs are placed using (4.9) and then the iterative algorithm is performed mentioned in Section 4.3.2. Simulation parameters are listed in Table. 4.1 unless stated otherwise. The results are analyzed by considering four different scenarios.

1. S-1: the priority is given to SBs demanding maximum data rate.
2. S-2: we give the priority to those, demanding minimum data rate and bandwidth.
3. S-3: SBs with highest spectral efficiency are prioritized.
4. S-4: All the SBs are given equal opportunity. In other words, the SB with highest SINR value will be considered first.

In the considered scenarios, the results are scrutinized for all the approaches (i.e., conventional approach [63], approach [64] and proposed approach).

Table. 4.2 demonstrates the performance in terms of the total associated SBs, average bandwidth consumption, sum rate of the overall system, SBs in the outage, average link utilization of all four child-UAVs, and energy efficiency, for conventional approach [63], approach [64], and the proposed approach. In general,

Table 4.1: Simulation Parameters

Parameter	**Value**	**Parameter**	**Value**
λ	0.15 m	ψ_{min}	-5 dB
β	0.16	σ_n	-125 dB
α	9.61	μ_{LoS}	1 dB
μ_{NLoS}	20 dB	I	1.1943×10^{-14} W
ς	$2 \times 10^{-6} / \text{ m}^2$	d_{min}	250 m
W_{c}	200×10^6 Hz	L	7
$\mathbf{r}_{SB}$	$\{20, 40, 60, 80, 100\}$ Mbps		

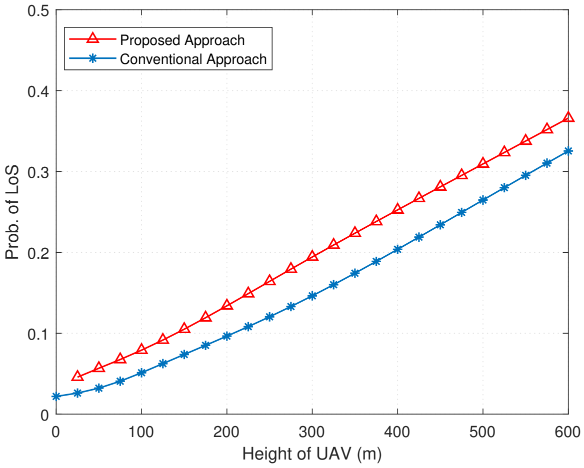

Figure 4.2: Impact of Height on avg. Probability of *LoS* for all child-UAVs.

Table 4.2: Comparison of Results with constraint $R_B = 1.40$ Gbps averaged over 1000 iterations.

Evaluation Parameters	**Conventional Approach [63]**			
	S-1	**S-2**	**S-3**	**S-4**
Total Associated SBs	17	20	17	19
Avg. BW Consumption (MHz)	185.30	179.44	185.30	171.50
Sum Rate (Gbps)	1.02	0.93	1.02	0.93
SBs in Outage	10	8	13	9
Avg. Link Utilization (%)	62.53	70.44	62	67.67
Energy Efficiency (η_{EE} (Mbps/W))	200.61	162.28	200.61	169.50

Evaluation Parameters	**Approach [64]**			
	S-1	**S-2**	**S-3**	**S-4**
Total Associated SBs	21	23	21	23
Avg. BW Consumption (MHz)	180.10	173.12	181.24	175.58
Sum Rate (Gbps)	1.38	1.19	1.38	1.29
SBs in Outage	7	5	7	5
Avg. Link Utilization (%)	75.23	82.01	75.18	81.23
Energy Efficiency (η_{EE} (Mbps/W))	225.06	179.11	226.94	194.90

Evaluation Parameters	**Proposed Approach**			
	S-1	**S-2**	**S-3**	**S-4**
Total Associated SBs	22	25	22	24
Avg. BW Consumption (MHz)	153.89	144.11	154.11	147.84
Sum Rate (Gbps)	1.39	1.39	1.39	1.39
SBs in Outage	6	3	6	4
Avg. Link Utilization (%)	78.41	89.25	78.37	85.69
Energy Efficiency (η_{EE} (Mbps/W))	218.93	192.71	227.64	200.72

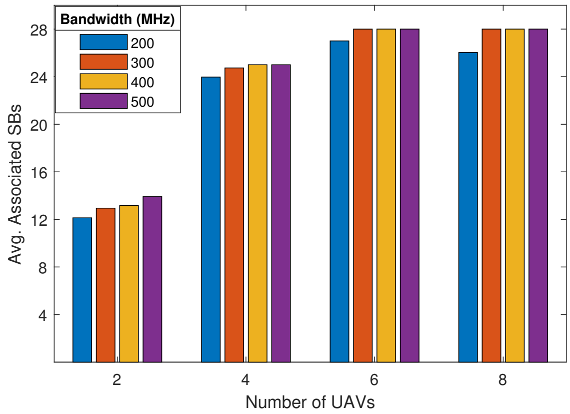

Figure 4.3: The bar plot of avg. associated SBs against No. of UAVs for proposed approach with constraint $R_B = 1.66$ Gbps averaged over 1000 iterations. (Scenario 1)

the proposed approach associated the highest number of SBs, maximized sum rate and energy efficiency in all scenarios by consuming less amount of bandwidth. Additionally, it can be observed that in the proposed approach, few SBs go into outage because the sum rate has maximized and we cannot serve more requests due to the constraint of backhaul data rate. However, if we increase the backhaul data rate limit then more SBs can be accommodated until the availability of bandwidth resource at each child-UAV. Conversely, the conventional approach [63] and approach [64] results in accommodating less SBs, consuming more bandwidth resource, achieving low sum rate and average link utilization.

Fig. 4.2 shows that how the proposed approach for the optimum placement of UAVs outperforms the conventional approach [63] in terms of probability of line-of-sight (LoS) when the height increases to 600 $meters$. This probability plays a vital role in reducing the average path-loss; thus improves the SINR.

Fig. 4.3 exhibits the performance of associating SBs by increasing the number of UAVs and their bandwidth W_c resource. It can be observed that four UAVs can-

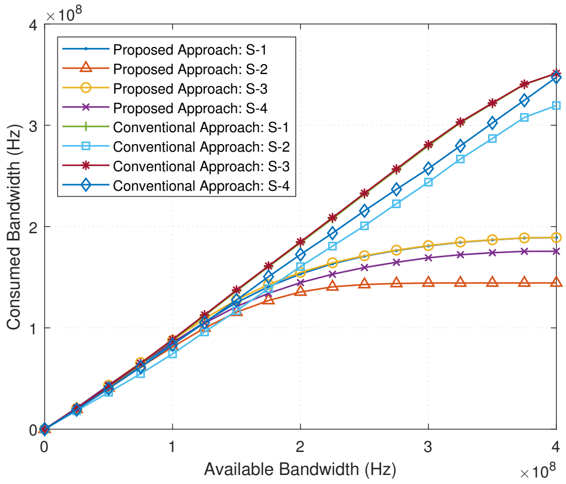

Figure 4.4: Bandwidth (W_c) vs. Sum Rate in Proposed Approach with constraint $R_B = 1.66$ Gbps averaged over 1000 iterations for all scenarios.

not cover the entire network, and therefore, few SBs go into the outage. However, six UAVs with the bandwidth of 300MHz can provide the services to the entire network.

Fig. 4.4 reveals that the sum rate of the system increases as the bandwidth resource increases for each UAV. The trend shows that the proposed approach's sum rate increases exponentially whereas the conventional approach's [63] increases linearly; thus proposed approach outperforms the conventional approach [63] in all the scenarios. Here, it can be concluded that the conventional approach [63] is bandwidth-hungry as compared to our proposed approach. For example, at the bandwidth of 400MHz, the performance of the conventional approach [63] touches the proposed one.

Fig. 4.5 unveils that the energy efficiency of the overall network improves as the number of UAVs increases. This is because, as the number of UAVs increases, coverage probability of serving SBs increases which results in increasing

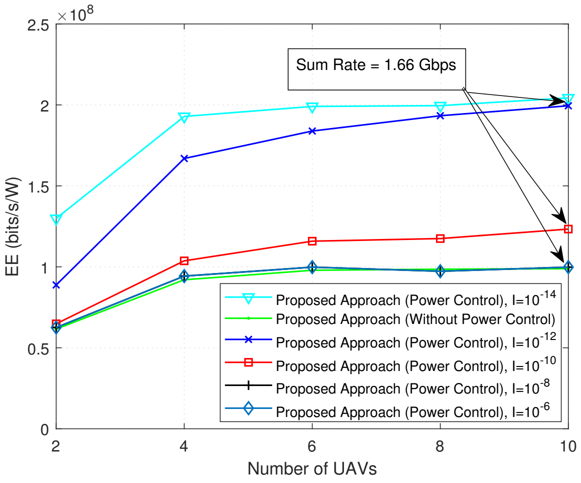

Figure 4.5: No. of UAVs vs. Energy Efficiency in Proposed Approach with constraint $R_B = 1.66$ Gbps averaged over 1000 iterations. (Scenario 2)

sum rate, and hence the trend of EE gets better. Also, the curves depict that as the interference threshold decreases, the corresponding transmits power of the child-UAVs decreases, which reduces the interference at each child-UAV, and therefore, EE increases. Moreover, no-power-control strategy meets the performance of power-control when the interference threshold goes beyond 10^{-8}. By limiting the transmit power of child-UAVs to an optimal value, interference from other child-UAVs reduces, which boosts SINR; therefore improving energy efficiency.

Fig. 4.6 gives the comparison between available bandwidth at each child-UAV and the averaged consumed bandwidth by all the UAVs. It can be noticed that the conventional approach's [63] average bandwidth consumption increases linearly, for all kinds of scenarios. On the other hand, the proposed approach (Mathod-1) consumes less bandwidth, in all the scenarios, and stops consuming the more bandwidth after approximately 170MHz because the objective has achieved at that point, whereas the conventional approach consuming more bandwidth to achieve

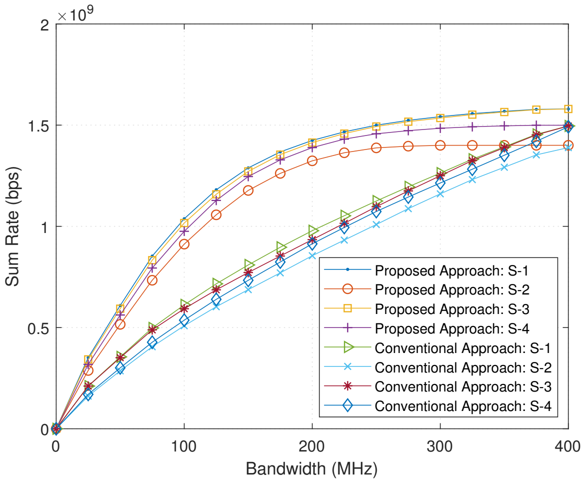

Figure 4.6: Available Bandwidth W_c vs. avg. Consumed Bandwidth in Proposed Approach with constraint $R_B = 1.40$ Gbps averaged over 1000 iterations.

the objective. Thus, it can be concluded that the conventional approach [63] is bandwidth-hungry.

Chapter 5

Conclusion and Future Work

The thesis is concluded in two parts as:

- We presented the efficient placement of UAVs to provide backhaul connectivity to ground SCBSs with the ground core network using unsupervised learning. The association of these SCBSs with the UAVs is limited by some factors including backhaul data rate limit, requests that each UAV can accommodate, the bandwidth available to each UAV, and minimum SINR criterion to meet QoS requirements. Further, the association is done based on three different demands: maximum data rate, minimum data rate plus bandwidth, and higher spectral efficiency. By considering the distribution of SCBSs, the proposed optimum placement of UAVs results in serving more requests by using less bandwidth, and good utilization of links by keeping in mind the objective function as compared to the existing approach presented in the literature.
- The extended version of the above problem is solved using the two-layer

framework, i.e., unsupervised learning and iterative algorithm. The communication link between SCBSs and child-UAVs is limited by many communication-related factors including bandwidth resource available to each child-UAV, number of links that each child-UAV can support, and minimum SINR criteria to satisfy QoS requirements. Additionally, the backhaul data rate limit for the link between parent-UAV and ground core-network. By considering these parameters, the association is done and results are investigated for four different scenarios, i.e., maximum data rate demand, minimum data rate plus bandwidth demand, higher spectral efficiency, and based on maximum SINR. The results show that the proposed optimum placement of child-UAVs outperforms the conventional placement in all scenarios at some computation cost.

In the future, we will also consider the hover time of UAV in the list of communication constraints. Also, the stochastic geometry of the association problem will be addressed such that the mathematical derivations of the simulated work of this thesis can be obtained. Further, we will use optimal transport theory to obtain delay optimal association of SCBSs with UAVs. Moreover, the closed-form solution of optimization problems discussed in Chapters 3 and 4 will be obtained to compare the results of theoretical versus simulation-based worked.

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