B.E Information Technology
PROJECT REPORT

DEPARTMENT OF INFORMATION TECHNOLOGY

JADAVPUR UNIVERSITY

Salt Lake Campus

.

OPTIMIZING ENERGY EFFICIENCY IN UAVs, USED IN COMMUNICATION NETWORKS

Project report submitted
in partial fulfillment of the requirement for the degree of

Bachelor of Engineering in Information Technology

By

Koushik Mahanta
(Class Roll No: 002011001106)
(Exam Roll No: ITE248077)

Dishari Saha
(Class Roll No: 002011001107)
(Exam Roll No: ITE248063)

Tusar Mundhra
(Class Roll No: 002011001122)
(Exam Roll No: ITE248072)

Under the guidance of

Mr. Palash Kundu

Department of Information Technology
Faculty of Engineering and Technology
Jadavpur University, Salt Lake Campus
2020-2024

.

Department of Information Technology
Faculty of Engineering and Technology
Jadavpur University

BONAFIDE CERTIFICATE

This is to certify that this project report entitled **“ OPTIMIZING ENERGY EFFICIENCY IN UAVs, USED IN COMMUNICATION NETWORKS. ”** submitted to **Department of Information Technology, Jadavpur University, Salt Lake Campus, Kolkata**, is a bonafide record of work done by “ Koushik Mahanta **(Registration No: 153809 of 2020-2021) ,** Dishari Saha **(Registration No: 153810 of 2020-2021)** , Tusar Mundhra **(Registration No: 153824 of 2020-2021)”** under my supervision from **“19 July 2023”** to **“21 May 2024”**

(Signature of the Supervisor)
Palash Kundu
Assistant Professor
Jadavpur University

Countersigned By:

(Signature of the HoD)
Dr. Bibhas Chandra Dhara
HOD, Dept of Information Technology

.

Acknowledgment

We would like to acknowledge Mr. Palash Kundu for his unwavering guidance on "**OPTIMIZING ENERGY EFFICIENCY IN UAVS, USED IN COMMUNICATION NETWORKS .**"
Your mentorship has been nothing short of transformative. From the initial stages of brainstorming and planning to the intricate details of execution, your insights and expertise have illuminated our path and propelled us forward. Your dedication to fostering our growth and development has instilled in us a profound sense of confidence and determination.

Your willingness to invest your time and energy in our project has not gone unnoticed. Your constructive feedback, encouragement, and willingness to go above and beyond to assist us have been instrumental in overcoming challenges and achieving milestones. Your mentorship has not only enhanced the quality of our project but has also enriched our understanding of the subject matter and expanded our horizons.

As we prepare to showcase our hard work and dedication, we are filled with gratitude for the opportunity to have worked under your guidance. Your influence has left an indelible mark on our academic and professional journey, and for that, we are profoundly thankful. Last but not the least, we would also like to thank to the entire departmental staff of Jadavpur University and our HOD Dr. Bibhas Chandra Dhara for his extended support.

Department of Information Technology
Jadavpur University
Salt Lake Campus, Kolkata

Koushik Mahanta Dishari Saha Tusar Mundhra

JADAVPUR UNIVERSITY
Dept. of Information Technology

Vision:

To provide young undergraduate and postgraduate students a responsive research environment and quality education in Information Technology to contribute in education, industry and society at large.

Mission:

M1: To nurture and strengthen professional potential of undergraduate and postgraduate students to the highest level.

M2: To provide international standard infrastructure for quality teaching, research and development in Information Technology.

M3: To undertake research challenges to explore new vistas of Information and Communication Technology for sustainable development in a value-based society.

M4: To encourage teamwork for undertaking real life and global challenges.

Program Educational Objectives (PEOs):

Graduates should be able to:

PEO1: Demonstrate recognizable expertise to solve problems in the analysis, design, implementation and evaluation of smart, distributed, and secured software systems.

PEO2: Engage in the engineering profession globally, by contributing to the ethical, competent, and creative practice of theoretical and practical aspects of intelligent data engineering.

PEO3: Exhibit sustained learning capability and ability to adapt to a constantly changing field of Information Technology through professional development, and self-learning.

PEO4: Show leadership qualities and initiative to ethically advance professional and organizational goals through collaboration with others of diverse interdisciplinary backgrounds.

Mission - PEO matrix:

Ms/ PEOs	M1	M2	M3	M4
PEO1	3	2	2	1
PEO2	2	3	2	1
PEO3	2	2	3	1
PEO4	1	2	2	3

(3 – Strong, 2 – Moderate and 1 – Weak)

Program Specific Outcomes (PSOs):

At the end of the program a student will be able to:

PSO1: Apply the principles of theoretical and practical aspects of ever evolving Programming & Software Technology in solving real life problems efficiently.

PSO2: Develop secured software systems considering constantly changing paradigms of communication and computation of web enabled distributed Systems.

PSO3: Design ethical solutions of global challenges by applying intelligent data science & management techniques on suitable modern computational platforms through interdisciplinary collaboration.

Abstract

Using Unmanned Aerial Vehicles (UAVs) is a promising solution for cellular user offloading in dynamic hotspot scenarios such as stadium, traffic jam, concert, etc. Additionally, in situations such as floods or wars where access to normal communication network infrastructure is hindered, UAVs can serve as temporary infrastructure to provide high data rate communication. Given that UAVs may need to remain airborne for extended periods, energy efficiency is paramount. This paper focuses on optimising the energy efficiency (EE) of UAVs by optimising their transmission power across different Physical Resources Blocks and for different users and by differently clustering the users for power sharing for NOMA (Non-Orthogonal Multiple Access) technology. Energy efficiency is defined as the ratio of the total sum of data rates to the total power consumption. By enhancing these parameters, we aim to maximise the performance and longevity of UAV communication systems in 5G networks.

***Keywords*:** *UAV*; *offloading*; *hotspot; NOMA.*

Optimising Energy Efficiency in UAVs, Used in Communication Networks

Contents

1 Introduction

Unmanned aerial vehicles (UAVs) are transforming the landscape of telecommunications, with tech giants such as Facebook and Google leading the charge in deploying vast networks of UAVs to provide broadband connectivity to remote regions [1], [2]. Amazon is also delving into UAV technology to optimize delivery services and reduce delivery times [3]. In Europe, projects like Absolute are leveraging UAVs as aerial base stations to enhance network capacity and ensure public safety during major events [4]. UAVs are proving invaluable in the realm of the Internet of Things (IoT), aiding low-power transmitters in efficient data transmission [5], [6], and facilitating energy-efficient communication [7], [8]. Moreover, UAVs as low altitude platforms (LAPs) are being integrated into cellular networks to address issues such as cell overload, site outages, and capacity enhancement, as extensively studied in [9], [10], [11]. For a comprehensive overview of UAV-assisted wireless communication and networking, resources like [12] provide valuable insights.

1.1 Motivation

Recently, the application of UAVs in wireless communications has attracted great attention because of their high mobility, low cost, and flexible deployment [12]. In addition, due to the mobility of the UAV, a high probability line-of-sight (LoS) link can be formed between ground users and the UAV. Thus, UAVs as aerial base stations (BSs) [13], [14], [15] and relays [16], [17] have been extensively studied by researchers from the scientific and industrial circles. Motivated by the above discussion, we exploit UAVs to serve a group of users in an area.

With the widespread use of smart devices, mobile multimedia traffic (e.g., video and remote meetings) has increased exponentially in the network. Multimedia traffic accounted for more than 82% of the entire network traffic in 2021 [18]. Correspondingly, the UAV-enabled emergency network should provide stringent data rate guarantees for mobile multimedia traffic.

When a UAV is used as an aerial BS to provide emergency services, how to extend the service time of the UAV is an important issue, because the onboard battery of the UAV has limited energy. According to References [19], [20], the energy consumption of the UAV is related to its hovering altitude. Therefore, by carefully optimising the hovering altitude and resource allocation of the UAV, the energy consumption of the UAV can be reduced when transmitting the same amount of data. Inspired by this reason, in this paper, we consider a UAV as an aerial BS to serve a group of ground users with different data rate requirements, in the downlink. Our goal is to maximize the energy efficiency of the UAV by jointly optimizing the altitude, user clustering and resource allocation of the UAV while satisfying a the data rate requirement for each user.

1.2 Contributions

In this paper we produce a system model where we incorporate power domain NOMA to serve multiple users(two users for simplification) sharing the PRB.

We also try to give a sub-optimal algorithmic solution to the problem that can return the results in polynomial time bounds. At the end we give simulation results using the algorithm to demonstrate the efficiency of our approach.

Table 1: Symbols and Descriptions

Symbol	Description
$\hbar_n$	Wireless channel gain for air-to-ground link from UAV to UE n
g_n	Large-scale average path-loss
h_n	Small scale fading channel co-efficient
z	Height of the UAV from ground
(x_n, y_n)	Horizontal co-ordinate of nth UE
α	Path loss exponent
η	attenuation resulting from the NLoS connection
$Pr_{LOS}(n)$	Probability of having LoS link between UAV and the nth UE
a	Environmental parameter for Pr_{Los}
b	Environmental parameter for Pr_{Los}
θ_n	Elevation angle of the UAV w.r.t the nth UE
$Pr_{NLOS}(n)$	Probability of having NLoS link between UAV and nth UE
ω	A specific value for random variable $\lvert h_n\rvert^2$
K_n	Rician factor for nth user
$E[\lvert h_n\rvert^2]$	Expected value or average value of $\lvert h_n\rvert^2$
$I_0(\cdot)$	Zero-order modified Bessel function of the first kind
k_0	Rician factor at 0 radian elevation angle
$k_{\frac{\pi}{2}}$	Rician factor at $(\pi/2)$ radian elevation angle
ρ_j	Threshold data rate for jth service class
a_n^j	Binary association of user n with service class j
d_n	Distance between UAV and ground user n
$\mathcal{B}$	Total channel bandwidth available to the UAV
SCS	Subcarrier spacing
β	Bandwidth of a PRB
EE	Energy Efficiency
R_{total}	Sum of the data rates achieved by all the UEs
P_{total}	Total power consumed for wireless transmission
$P_{circuit}$	Circuit power consumption of the UAV
x_n^r	Binary association of user n with PRB r
x	$\{x_n^r \mid n \in \{1, 2, \ldots, N\},\ r \in \{1, 2, \ldots, R\}\}$
p_n^r	Transmitted signal power for user n in PRB r
p	$\{p_n^r \mid n \in \{1, 2, \ldots, N\},\ r \in \{1, 2, \ldots, R\}\}$
r_n^r	Data rate achieved by user n in PRB r
σ	Noise power density
r_n	Total data rate achieved by user n
P	Maximum transmit power available to the UAV
z_{min}	Minimum height of the UAV
z_{max}	Maximum height of the UAV

2 System Model

We consider a cellular system where a UAV provides wireless access to terrestrial mobile devices, serving as an aerial base station. We assume that there are N ground users uniformly distributed in the region to be served.

Each user can subscribe to only one of the J service classes available. The rate guaranteed for jth service class is given by ρ_j (threshold data rate). The rate that is being provided by the UAV to the user n is given by r_n. We use a binary variable a_n^j to represent the user-service class association. If the user n subscribed to

jth service class, then a_n^j is set to 1, otherwise 0. Each user can subscribe to only one service class, therefore

$$\sum_{j=1}^{J} a_n^j = 1, \forall n \in \{1, 2, ..., N\}$$

Without loss of generality, we build a 3D Cartesian coordinate system in which the location of each ground user is given by $\mathbf{u_n} = (x_n, y_n, 0), \forall n \in N$. In addition, we assume that the UAV is at coordinate $(0, 0, z)$. The flying altitude of the UAV is z. The distance between the UAV and the ground user n can be calculated as follows:

$$d_n = \sqrt{x_n^2 + y_n^2 + z^2} \tag{1}$$

Now, let $\mathcal{B}$ denote the total available transmission bandwidth which can be devided into Physical Resource Blocks (PRBs) according to LTE or 5G/NR frame structure requirements

Let's assume here that each PRB has a bandwidth of β. There can be at most R number of PRBs. Each user is assigned multiple PRBs according to the requirements of the user and each PRB is used to serve at most two users using power domain NOMA technology.

2.1 Channel Model

The wireless channel between the UAV and UE is assumed to experience small-scale fading and large-scale path loss. So, the air-to-ground (A2G) wireless channel gain from the UAV to the ground user n can be expressed as follows

$$\hbar_n = g_n |h_n|^2 \tag{2}$$

where, g_n denotes large-scale average path-loss and h_n represents small scale fading channel co-efficient. g_n is given by [21],

$$g_n = \begin{cases} \left(\sqrt{x_n^2 + y_n^2 + z^2}\right)^{-\alpha}, & \text{LOS Link} \\ \eta \left(\sqrt{x_n^2 + y_n^2 + z^2}\right)^{-\alpha}, & \text{NLOS Link} \end{cases} \tag{3}$$

where α is the path loss exponent for UAV-user links, and the term η represents the attenuation resulting from the Non-Line of Sight (NLOS) connection. The probability of having Line of Sight (LOS) link depends on the locations of the UAV and the UE, the environment parameters, and elevation angle θ_n . It can be found by the following formula [21],

$$Pr_{LOS}(n) = \frac{1}{1 + a \exp(-b[\frac{180}{\pi} \times \theta_n - a])} \tag{4}$$

where constants a and b are the environment parameters, and elevation angle θ_n of the UAV w.r.t the nth UE (measured in radian) is calculated as [21]

$$\theta_n = \sin^{-1}\left(\frac{z}{\sqrt{x_n^2 + y_n^2 + z^2}}\right) \tag{5}$$

Thus, the probability of having NLOS link is $Pr_{NLOS}(n) = 1 - Pr_{LOS}(n)$.Finally,$g_n$ is given by [21]:

$$g_n = Pr_{LOS}(n) \times \left(\sqrt{x_n^2 + y_n^2 + z^2}\right)^{-\alpha} + Pr_{NLOS}(n) \times \eta \left(\sqrt{x_n^2 + y_n^2 + z^2}\right)^{-\alpha} \tag{6}$$

In addition, we can model the small-scale fading channel from the UAV to any ground user n as the Rician fading, because there are usually a dominant LoS component and multipath scatterers. Using this model, h_n has the circularly symmetric complex Gaussian distribution $\mathcal{CN}(0, 1)$. According to [22], $|h_n|^2$ is the small-scale power gain which obeys the noncentral chi-square distribution and is with a normalized average power $E[|h_n|^2] = 1$. Thus, the probability distribution function (PDF) of $|h_n|^2$ can be written as follows:

$$f_{|h_n|^2}(\omega) = \frac{(K_n + 1)e^{-K_n}}{E[|h_n|^2]} \exp\left(\frac{-(K_n + 1)\omega}{E[|h_n|^2]}\right) \times I_0\left(2\sqrt{\frac{K_n(K_n + 1)\omega}{E[|h_n|^2]}}\right), \omega \geq 0 \tag{7}$$

where I_0 denotes the zero-order modified Bessel function of the first kind and K_n is the Rician factor.

The Rician factor(K_n) for the distribution depends on the environmental factors and the elevation angle of the UAV w.r.t the user n. K_n is calculated using the given formula [11],

$$K_n = a_2 \times e^{b_2 \theta_n} \tag{8}$$

where, θ_n is the elevation angle of the UAV w.r.t user n in radian. a_2 and b_2 are are environment and frequency dependent constant parameters which are given by the equations [11],

$$a_2 = k_0,\ b_2 = \frac{2}{\pi} \ln \left(\frac{k_{\frac{\pi}{2}}}{k_0} \right) \tag{9}$$

where, k_0 is rician factor at 0 radian elevation angle and $k_{\frac{\pi}{2}}$ is rician factor at $(\pi/2)$ radian elevation angle.

2.2 User Clustering

For creating pairs of users who will be served using the same PRB, we sort the users according to their respective channel gains ($\hbar_n$) such that $\hbar_1 > \hbar_2 > \hbar_3 > \cdots > \hbar_N$. We then devide this list into two equal halves, first half consisting of users $\{u_1, u_2, u_3, \ldots, u_{N/2}\}$ and second half consisting of users $\{u_{N/2+1}, u_{N/2+2}, u_{N/2+3}, \ldots, u_N\}$

For clustering (pairing in this case) we only consider the two users that belong to the different halves of the list, that is, two users belonging to the same half are not paired for sharing a PRB. But, a single user can be paired with multiple users, provided, they belong to different halves of the list. For simplicity, we assume N to be an even integer.

This clustering method ensures that users will be able to decode the received signal by employing Successive Interference Cancellation(SIC) mechanism.

2.3 Objective

We aim to develop an algorithm for deciding optimal user clustering, power allocation and UAV height that maximizes the energy efficiency. We define Energy Efficiency (EE) as the total sum of achieved data rates (R_{total}) divided by the summation of total transmit power (P_{total}) and total circuit power ($P_{circuit}$) consumption:

$$EE = \frac{R_{total}}{P_{total} + P_{circuit}}$$

2.4 Achieved Data Rate

For facilitating user clustering, power allocation and ultimately data rate calculation for the purpose of problem formulation we define a binary variable x_n^r which is set to 1 if PRB r is allocated to user n and a real variable p_n^r that takes the value of the transmission power allocated to user n in PRB r. $\boldsymbol{x} \triangleq \{x_n^r \mid n \in \{1, 2, \ldots, N\},\ r \in \{1, 2, \ldots, R\}\}$, and $\boldsymbol{p} \triangleq \{p_n^r \mid n \in \{1, 2, \ldots, N\},\ r \in \{1, 2, \ldots, R\}\}$.

We previously sorted the users such that $\hbar_1 > \hbar_2 > \hbar_3 > \cdots > \hbar_N$ and user n can face interference in a PRB only from those users that have higher channel gains and are allocated the same PRB as n. That means user n will face interference in PRB r from all users m such that $m \in \{1, 2, ..., n-1\}$ and x_m^r = 1.

Assuming additive white Gaussian noise (AWGN) channel, the achievable rate of user n in PRB r is given by,

$$r_n^r = \beta \log_2 \left(1 + \frac{p_n^r \hbar_n}{\sigma\beta + \sum_{i=0}^{n-1} x_i^r p_i^r \hbar_n} \right) \tag{10}$$

where σ is the noise power density, so $\sigma\beta$ is the noise power over the bandwidth β, p_n^r is the transmission power of the signal for user n in PRB r.

So, the total data rate for user n is,

$$r_n = \sum_{r=1}^{R} r_n^r x_n^r \tag{11}$$

The total data rate realized by all the users combined is,

$$R_{total} = \sum_{n=1}^{N} r_n \tag{12}$$

and the total power consumed for transmission is,

$$P_{total} = \sum_{r=1}^{R} \sum_{n=1}^{N} p_n^r \tag{13}$$

2.5 Problem Formulation

The optimization problem is to find the optimal values of PRB allocation ($\boldsymbol{x}$), power allocation ($\boldsymbol{p}$) and UAV altitude (z) with the objective of maximizing energy efficiency while satisfying the user data rate requirements. The optimization problem can be mathematically formulated as problem (14).

$$\max_{(\boldsymbol{x},\boldsymbol{p},z)} \left(\frac{R_{total}}{P_{total} + P_{circuit}} \right), \tag{14a}$$

$$s.t. \sum_{n=1}^{N} x_n^r = 2, \forall r \in \{1, 2, \dots, R\}, \tag{14b}$$

$$r_n \geq \sum_{j=1}^{J} a_n^j \rho_j, \forall n \in \{1, 2, \dots, N\}, \tag{14c}$$

$$\sum_{j=1}^{J} a_n^j = 1, \forall n \in \{1, 2, \dots, N\}, \tag{14d}$$

$$p_{total} \leq P, \tag{14e}$$

$$p_n^r > 0, \forall (n, r) \in \{(n, r) | \, x_n^r = 1\}, \tag{14f}$$

$$z_{min} \leq z \leq z_{max} \tag{14g}$$

$$a_n^j \in \{0, 1\}, \forall n \in \{1, 2, \dots, N\}, j \in \{1, 2, \dots, J\} \tag{14h}$$

$$x_n^r \in \{0, 1\}, \forall n \in \{1, 2, \dots, N\}, r \in \{1, 2, \dots, R\} \tag{14i}$$

In this context, P denotes the maximum transmit power of the UAV, and z_{max} and z_{min} represent the maximum and minimum permitted flying altitudes, respectively. Constraint (14b) ensures that each PRB is allocated to exactly two users. Constraint (14c) requires that each user achieves a data rate that meets or exceeds the specified threshold. Constraint (14d) stipulates that each user may subscribe to only one service class. Constraint (14e) ensures that the total power allocated by the UAV does not exceed its maximum transmit power. Constraint (14f) mandates non-zero power allocation to each user in every PRB they are served with. Constraint (14g) bounds the UAV's flying altitude within the specified minimum and maximum limits. Lastly, constraints (14h) and (14i) dictate that the variables a_n^j and x_n^r can only take binary values, either 0 or 1.

3 Proposed Solution

As we can see the optimization problem (14) is a non-convex, mixed-integer, non-linear optimization problem it can not be solved for an optimal solution in polynomial time complexity bounds. So, we use an heuristic approach for finding a sub-optimal solution which as we will show works well.

Algorithm 1 Proposed Algorithm

Require: $R,\ P,\ \beta,\ \sigma,\ z,\ z_{min},\ z_{max},\ \mathcal{U} = \{u_0, u_1, u_2, \ldots, u_{n-1}\},\ \mathcal{R} = \{\rho_0, \rho_1, \rho_2, \ldots, \rho_{n-1}\},$ $\mathcal{C} = \{(x_0, y_0), (x_1, y_1), (x_2, y_2), \ldots, (x_N, y_N)\}$, Environmental Parameters

Calculate $\mathcal{H} = \{\hbar_0, \hbar_1, \hbar_2, \ldots, \hbar_{n-1}\}$ using $\mathcal{C}$, z and Environmental Parameters
Sort the users in $\mathcal{U}$ such that $\hbar_0 > \hbar_1 > \cdots > \hbar_{n-1}$
▷ **PRB Requirements Estimation**
for $i = 0$ to $n - 1$ **do**
 $x_i \leftarrow \frac{\rho_i}{|\hbar_i|}$
end for
for $i = 0$ to $n - 1$ **do**
 $v[i] \leftarrow \lceil \frac{x_i}{\sum_{j=1}^{n} x_i} 2R \rceil$
end for
▷ **User Clustering**
$r \leftarrow R$
$k \leftarrow 0$
$l \leftarrow \lceil n/2 \rceil$
while $r > 0$ **and** $\sum_{i=0}^{\lceil n/2 \rceil - 1} v[i] \neq 0$ **and** $\sum_{i=\lceil n/2 \rceil}^{n-1} v[i] \neq 0$ **do**
 while $v[k \mod \lceil n/2 \rceil] = 0$ **do**
  $k \leftarrow k + 1$
 end while
 while $v[\lceil n/2 \rceil + (l \mod \lceil n/2 \rceil)] = 0$ **do**
  $l \leftarrow l + 1$
 end while
 $i \leftarrow k \mod \lceil n/2 \rceil$
 $j \leftarrow \lceil n/2 \rceil + (l \mod \lceil n/2 \rceil)$
 $association[i, j] \leftarrow association[i, j] + 1$
 $user\_first[i] \leftarrow user\_first[i] + 1$
 $user\_second[j] \leftarrow user\_second[j] + 1$
 $r \leftarrow r - 1$
 $v[i] \leftarrow v[i] - 1$
 $v[j] \leftarrow v[j] - 1$
 $k \leftarrow k + 1$
 $l \leftarrow l + 1$
end while
▷ **Power Allocation**
$i \leftarrow 0$
while $i < n$ **do**
 if $user\_first[i] \neq 0$ **then**
  $TotalPRB \leftarrow user\_first[i] + user\_second[i]$
  $avg\_rate \leftarrow \rho_i / TotalPRB$
  $power\_first \leftarrow 10 \log_{10}(2^{avg\_rate/\beta} - 1) + \sigma + 10 \log_{10} \beta - \hbar_i$
  $j \leftarrow 0$
  while $j < n$ **do**
   if $association[i, j] \neq 0$ **then**
    $power[i, j, 0] \leftarrow power\_first$
   end if
   $j \leftarrow j + 1$
  end while
 end if
 $i \leftarrow i + 1$
end while

48: $i \leftarrow 0$
49: **while** $i < n$ **do**
50:     **if** $user\_second[i] \neq 0$ **then**
51:         $TotalPRB \leftarrow user\_second[i] + user\_first[i]$
52:         $avg\_rate \leftarrow \rho_i / TotalPRB$
53:         $j \leftarrow 0$
54:         **while** $j < n$ **do**
55:             **if** $association[j, i] \neq 0$ **then**
56:                 $interfering\_power\_linear \leftarrow 10^{(power[j,i,0]/10)}$
57:                 $H_l inear \leftarrow 10^{(\hbar_i/10)}$
58:                 $\sigma_{linear} \leftarrow 10^{(\sigma/10)}$
59:                 $power[j, i, 1] \leftarrow 10\log_{10}(2^{avg\_rate/\beta} - 1) + 10\log_{10}(interfering\_power\_linear \times H_{linear} + \sigma_{linear} \times \beta) - \hbar_i$
60:             **end if**
61:             $j \leftarrow j + 1$
62:         **end while**
63:     **end if**
64:     $i \leftarrow i + 1$
65: **end while**
66: Repeat steps (1) through (65) and calculate the objective function value for all $z \in \{z_{min}, z_{min} + 1, z_{min} + 2, \ldots, z_{max}\}$
67: return the set $\{z, association, power\}$ that satisfies, $P_{total} \leq P$ and maximizes the objective function

The algorithm (1) listing depicts the algorithm for finding the solution. In this algorithm we assume that, $\hbar_n$ is in dB unit and power is in dBm unit.

In the algorithm we try to use a heuristic approach to tackle the problem. We calculate a quantity $x_i = \rho_i / |\hbar_i|$ and calculate a heuristic $\lceil 2R\frac{x_i}{\sum_i x_i} \rceil$ to estimate the number of PRBs that is required by user i, where $\rho_i, \hbar_i$ and R are the threshold data rate of user i, channel gain of user i and total number of PRBs, respectively.

We take a list of users, their required threshold data rates, their location w.r.t the UAV and some system and environment parameters as input. Using these input we first calculate their respective air-to-ground channel gain and then sort the list of users in descending order of their channel gains, for the user clustering process. We cluster the users using the clustering scheme mentioned previously by dividing the list into two equal halves and pairing users in different halves only, while keeping in mind the number of PRBs still available and the estimated number of PRBs required by each user. We do this clustering iteratively until all the PRBs are exhausted or until users of one half have zero PRB requirement.

After the user clustering process is completed we assign power to each user so that their data rate requirements are satisfied. First, we assign power to the user with higher channel gain in each PRB, let's call them "1st user" of a PRB. We calculate the total number of PRBs assigned to each 1st user. Then we calculate the average data rate that should be satisfied by each PRB to satisfy the total data rate requirement of that user. Using this average data rate we calculate the power required by the user in each PRB it is assigned as a 1st user to satisfy that rate, and we assign this power to the user in those PRBs where it is the 1st user.

Then in the same way we calcualte the average data rate of users that has lower channel gains in each PRBs (let's call them 2nd users). Using this rate and the already calculated 1st user's power we can easily calculate the 2nd user's power in each PRB.

We repeat the above steps for all UAV altitude values $z \in \{z_{min}, z_{min} + 1, z_{min} + 2, \ldots, z_{max}\}$ and we take the set $\{z, association, power\}$ that satisfies, $P_{total} \leq P$ and maximizes the objective function.

3.1 Time Complexity

- line (1) of the algorithm calculates channel gain for each user. For each user this takes constant time. There are total n users, so time complexity of the first line is $\mathcal{O}(n)$

- line (2) sorts the users, it has complexity $\mathcal{O}(n \log n)$
- line (4) indicates the beginning of a loop that executes n times, each time doing constant amount of work. So, its time complexity is also $\mathcal{O}(n)$
- line (7) also indicates the beginning of a loop and in a similar way also has a time complexity $\mathcal{O}(n)$
- line (11, 12, 13) executes single constant time operation. So their time complexity is $\mathcal{O}(1)$
- line (14) again indicates the beginning of a loop that can execute at most R times. This loop also has two inner-loops.
  - the first inner-loop beginning at line (15) can execute $\lceil n/2 \rceil$ times in the worst case, contributing a time complexity of $\mathcal{O}(n/2)$
  - likewise the second inner-loop beginning at line (18) can also execute $\lceil n/2 \rceil$ times in the worst case, also having a time complexity of $\mathcal{O}(n/2)$

  lines (21 - 30) execute constant time operations. So, the entire loop beginning at line (14) has complexity $\mathcal{O}(R \cdot n)$
- line (33) executes constant time operation
- line (34) indicates the entrance of another loop that executes n times. It has an inner-loop that can also execute at most n times. Making the complexity of the outer-loop $\mathcal{O}(n^2)$
- line (48) executes constant time operation
- line (49) again indicates the beginning of a loop which is similar to the loop at line (34) except some constant time operations. So, it also has a complexity of $\mathcal{O}(n^2)$
- up to this point the complexity is

$$complexity = \begin{cases} \mathcal{O}(R \cdot n), & \text{if } R \geq n \\ \mathcal{O}(n^2), & \text{Otherwise} \end{cases}$$

- all the previous operations will be repeated for different heights. So,

$$complexity = \begin{cases} \mathcal{O}(y \cdot R \cdot n), & \text{if } R \geq n \\ \mathcal{O}(y \cdot n^2), & \text{Otherwise} \end{cases}$$

  where, $y = z_{max} - z_{min} + 1$

4 Simulation and Result

For the simulation process we have considered four service classes, namely,

- Downloading videos through social media: 25 Mbps for streaming UHD 4K video
- Video conferencing: 5 Mbps
- Live broadcasting: 3 Mbps
- Emails/Web surfing/VoIP calling: 1 Mbps

In the table below we mention all the system and environment parameter values used for the simulation according [11], [21] and [22].

Table 2: Simulation Parameters

Parameter	**Value**	**Parameter**	**Value**
α	3	η	20 dB
k_0	5 dB	$k_{\frac{\pi}{2}}$	15 dB
a	11.95	b	0.136
SCS	60 kHz	σ	-174 dBm
β	720 kHz	$\mathcal{B}$	100 MHz
P	46 dBm	$P_{circuit}$	13.01 dBm
z_{min}	10 m	z_{max}	132 m

Following are the results of running the python implementation of the solution:

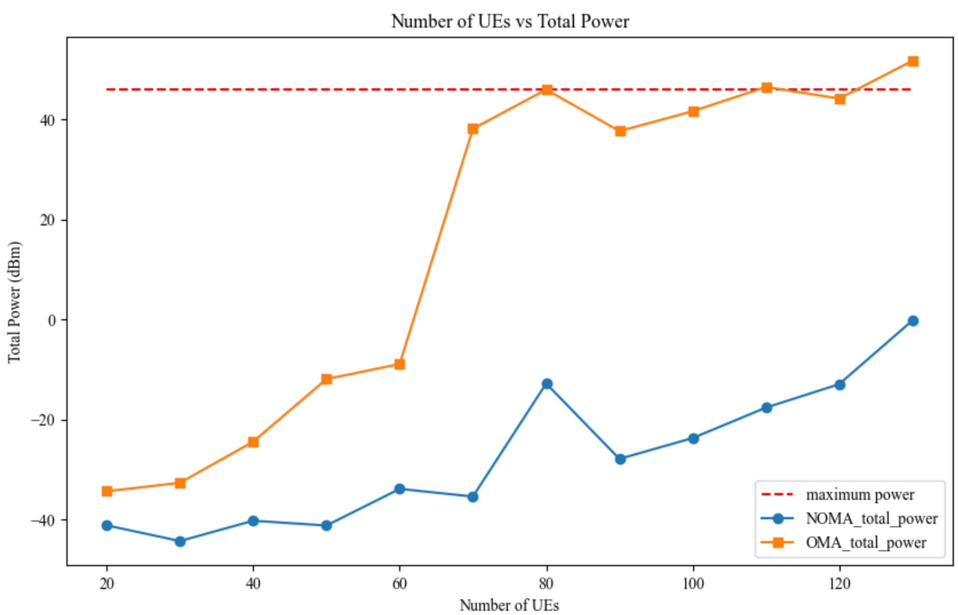

Figure 1: Number of UEs vs Total Power consumed for transmission. Here the power is in dBm units for better visual comparison

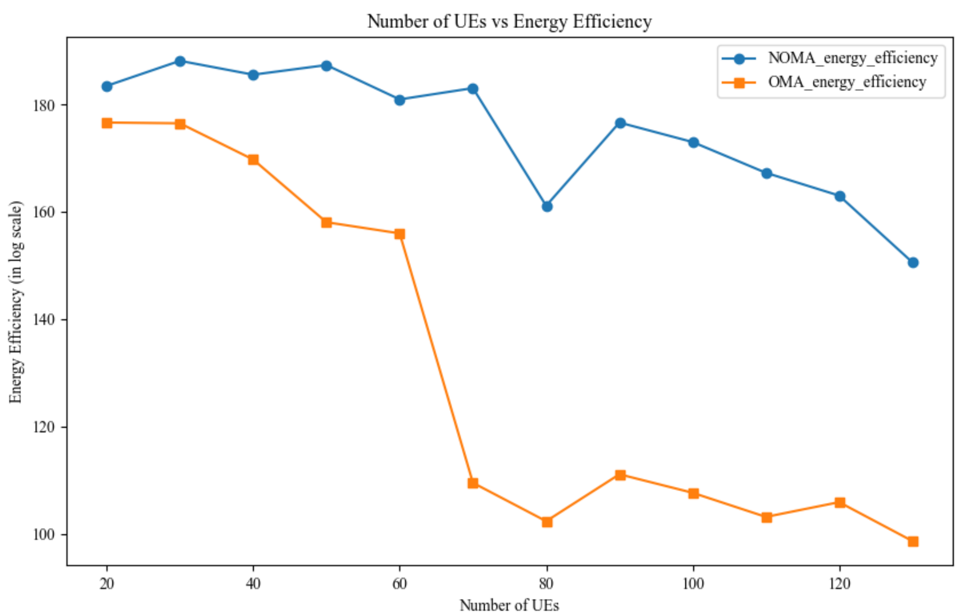

Figure 2: Number of UEs vs Energy Efficiency (defined previously). Here the Energy Efficiency is represented in logarithmic scale for better visual representation

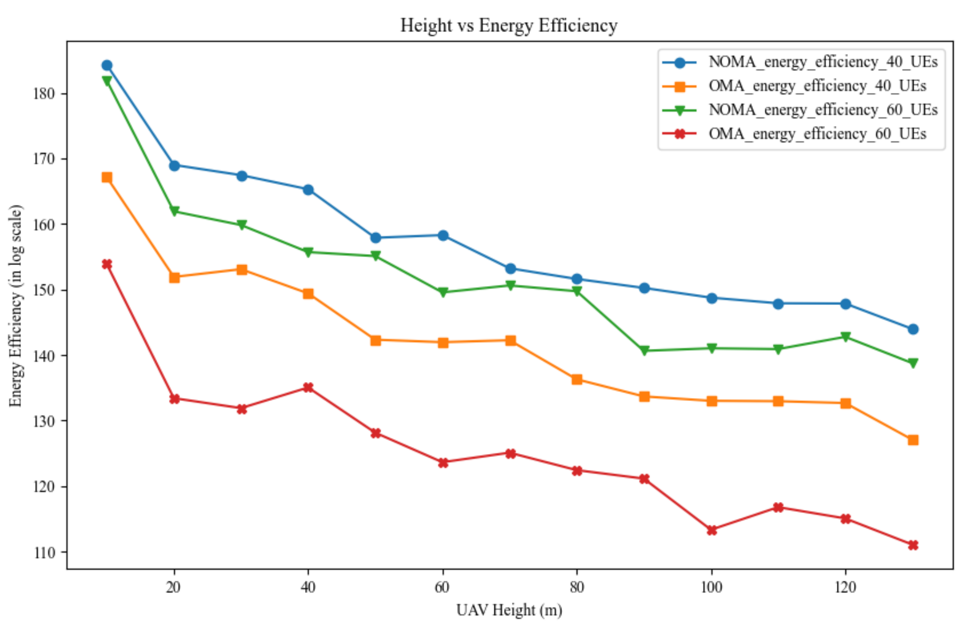

Figure 3: Height vs Energy Efficiency (defined previously). Here the Energy Efficiency is represented in logarithmic scale for better visual representation

5 Conclusion and Future Scope

In this paper we have proposed an algorithm for maximizing energy efficiency of UAVs used in NOMA based communication networks by optimizing user clustering, power allocation and UAV altitude. To the best of our knowledge this is the first study in the area of energy efficiency maximization of UAVs in NOMA based networks. We have formulated the problem and then provided an heuristic algorithm that solves for a sub-optimal result in polynomial time. Through numerical results we showed that our approach gives significant improvements compared to an OMA (Orthogonal Multiple Access) based approach. For future works one might consider clustering more than two users for sharing a PRB, which will introduce more granularity in the system facilitating further optimisation and better Energy Efficiency.

References

[1] Facebook, "Connecting the world from the sky," Facebook, Cambridge, MA, USA, Tech. Rep., 2014.

[2] S. Katikala, "Google project loon," *Sight, Rivier Acad. J.*, vol. 10, no. 2, 2014.

[3] "Amazon Prime Air," Online, 2015, available: http://www.amazon.com/b?node=8037720011.

[4] "Absolute (aerial base stations with opportunistic links for unexpected and temporary events)," Online, available: http://www.absolute-project.eu.

[5] S.-Y. Lien, K.-C. Chen, and Y. Lin, "Towards ubiquitous massive accesses in 3gpp m2m communications," *Communications Magazine, IEEE*, vol. 49, pp. 66 – 74, 05 2011.

[6] H. S. Dhillon, H. Huang, and H. Viswanathan, "Wide-area wireless communication challenges for the internet of things," *IEEE Communications Magazine*, vol. 55, no. 2, pp. 168–174, 2017.

[7] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Mobile unmanned aerial vehicles (uavs) for energy-efficient internet of things communications," *IEEE Transactions on Wireless Communications*, vol. 16, no. 11, pp. 7574–7589, 2017.

[8] Y. Zeng and R. Zhang, "Energy-efficient uav communication with trajectory optimization," *IEEE Transactions on Wireless Communications*, vol. 16, no. 6, pp. 3747–3760, 2017.

[9] S. Rohde and C. Wietfeld, "Interference aware positioning of aerial relays for cell overload and outage compensation," in *2012 IEEE Vehicular Technology Conference (VTC Fall)*, 2012, pp. 1–5.

[10] A. Merwaday and I. Guvenc, "Uav assisted heterogeneous networks for public safety communications," in *2015 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, 2015, pp. 329–334.

[11] M. M. Azari, F. Rosas, K.-C. Chen, and S. Pollin, "Ultra reliable uav communication using altitude and cooperation diversity," *IEEE Transactions on Communications*, vol. 66, no. 1, pp. 330–344, 2018.

[12] Y. Zeng, R. Zhang, and T. J. Lim, "Wireless communications with unmanned aerial vehicles: opportunities and challenges," *IEEE Communications Magazine*, vol. 54, no. 5, pp. 36–42, 2016.

[13] C. Zhang, L. Zhang, L. Zhu, T. Zhang, Z. Xiao, and X.-G. Xia, "3d deployment of multiple uav-mounted base stations for uav communications," *IEEE Transactions on Communications*, vol. 69, no. 4, pp. 2473–2488, 2021.

[14] T. Bai, C. Pan, J. Wang, Y. Deng, M. Elkashlan, A. Nallanathan, and L. Hanzo, "Dynamic aerial base station placement for minimum-delay communications," *IEEE Internet of Things Journal*, vol. 8, no. 3, pp. 1623–1635, 2021.

[15] X. Jing, J. Sun, and C. Masouros, "Energy aware trajectory optimization for aerial base stations," *IEEE Transactions on Communications*, vol. 69, no. 5, pp. 3352–3366, 2021.

[16] Z. Sheng, H. D. Tuan, T. Q. Duong, and L. Hanzo, "Uav-aided two-way multi-user relaying," *IEEE Transactions on Communications*, vol. 69, no. 1, pp. 246–260, 2021.

[17] B. Yang, T. Taleb, Y. Fan, and S. Shen, "Mode selection and cooperative jamming for covert communication in d2d underlaid uav networks," *IEEE Network*, vol. 35, no. 2, pp. 104–111, 2021.

[18] G. Forecast, "Cisco visual networking index: Global mobile data traffic forecast update, 2017–2022," *Update*, vol. 2017, p. 2022, 2019.

[19] N. Babu, K. Ntougias, C. B. Papadias, and P. Popovski, "Energy efficient altitude optimization of an aerial access point," in *2020 IEEE 31st Annual International Symposium on Personal, Indoor and Mobile Radio Communications*, 2020, pp. 1–7.

[20] H. V. Abeywickrama, B. A. Jayawickrama, Y. He, and E. Dutkiewicz, "Comprehensive energy consumption model for unmanned aerial vehicles, based on empirical studies of battery performance," *IEEE Access*, vol. 6, pp. 58 383–58 394, 2018.

[21] H. Wang, J. Chen, G. Ding, and S. Wang, "D2d communications underlaying uav-assisted access networks," *IEEE Access*, vol. 6, pp. 46 244–46 255, 2018.

[22] H. Niu, X. Zhao, L. Hou, and D. Ma, "Energy efficiency maximization for uav-assisted emergency communication networks," *Wireless Communications and Mobile Computing*, vol. 2021, p. 7595347, Aug 2021. [Online]. Available: https://doi.org/10.1155/2021/7595347