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RESEARCH ARTICLE

Combinatorial Resource Allocation in UAV-Assisted 5G/B5G Heterogeneous Networks

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ABSTRACT The advancements in technology have greatly influenced our daily lives and have brought about numerous changes in the way we live, work, and communicate. The rise of social media platforms has resulted in the transformation of the ways people interact and share information. Therefore existing terrestrial infrastructure needs to be replaced by modern communication means. Unmanned aerial vehicles (UAVs) have proved their potential to play a significant role in heterogeneous networks (HetNets) by providing additional coverage and capacity in areas that are crowded or hit by any natural disaster due to several associated advantages. This work has presented an optimized resource allocation problem in UAV-assisted HetNet. An outer approximation(OAA) based novel algorithm has been proposed to solve the presented mixed integer nonlinear programming problem (MINLP). Complexity Comparison of the proposed algorithm with other state-of-the-art methods is presented. The Prime objective is to maximize the network data rate subject to the constraints of power and Quality of service (QoS). Extensive simulation work is performed to compare the UAV-assisted HetNet data rate and associated users with Macro-only scenarios. Results have proved the outperformance of the proposed algorithm. UAV-assisted HetNet data rate and associated users are also investigated for different Quality of service (QoS) requirements and results have proved that the proposed OAA algorithm has still maintained its outperformance as compared to conventional HetNets. The result section also includes the simulation results of the comparison between the proposed OAA-based algorithm with other state-of-the-art methods.

INDEX TERMS Heterogeneous networks (HetNet), maximal weighted area (MWA), outer approximation algorithm (OAA), quality of service (QoS), recall frequency (RF), unmanned aerial vehicle (UAV), mesh adaptive direct search (MADS).

I. INTRODUCTION

The emergence of high data rate demanding applications like video streaming, online gaming, and several other multimedia applications require an evolution of new technological trends for communication. Data rate requirement has evolved from Kbps to Gbps within a few decades. To satisfy these high data rate requirements technology has made a shift towards a 5G communication infrastructure. Key 5G features include: connected Devices 10-100X, data Volume 1000X, low latency value, delay less than 1ms, availability and Reliability 99.99. Several technologies have evolved with the passage of time to satisfy high-demanding 5G network requirements. These technologies involve cell densification, massive MIMO, and mm-wave communication [16]. Cell densification is basically the addition of smaller cells (micro, femto, pico, and nano) within the same existing macro cell structure.

The key idea in cell densification is to reuse the same frequency spectrum to enhance the network capacity. Latency is also minimized in this architecture because the end-user is coming closer to the base station. Day by day with the emergence of a high data rate demanding applications existing spectrum is becoming an overcrowded resource.

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In the current situation in order to provide a better communication experience, it is required to utilize the new spectrum avenues e.g., the mm-wave range (30-300GHz). Another technology used for 5G communication is M-MIMO [17]. It enhanced spectral utilization efficiency by using spatial diversity. It transmits and receives multiple users' data over the same radio resource. However, each technology has its own limitations. The cell densification technique offers spectral efficiency but it also causes interference and high power utilization problems. Therefore, energy and both co/cross-tier interference management is a serious concern for cell densification. LoS communication, high transmission losses, and transmitter and receiver hardware manufacturing are serious concerns for mm-wave communication [18].

With cutting-edge requirements of high performance for communication systems of next-generation (5G and beyond 5G), network coverage and throughput maximization have always been among the leading issues. Sometimes, there is a situation in which a large group of end-users demanding connectivity along with a high data rate suddenly appear in a certain specific location e.g., in a stadium. This demands the addition of more base stations to that specific location to satisfy the end-user's demands. However, this new base station deployment is an expensive solution and also requires the network to be re-planned completely. This problem can simply be handled by the addition of UAV-assisted base stations in already deployed wireless communication systems [1]. The UAV-assisted base station is also the best suitable candidate to provide rescue and coverage services in natural disasters or hard areas where terrestrial infrastructure has vanished due to disaster situations.

UAVs are usually very quick to be deployed, and more easily reconfigured and they have good communication channel scenarios because of the presence of a shortening line of sight channels. Also, features like maneuverability and adaptive communication make UAV-assisted communication a suitable and efficient option for future technologies e.g., 5G and beyond wireless communication networks. The UAV-BS could serve in numerous situations, for example, if there is some kind of malfunction in terrestrial wireless communication infrastructure or if traffic off-loading is required from an overloaded macro BS. UAVs find their application in wireless communication as flying base stations, relay nodes, and flying user equipment [1]. Recently UAVs have proved themselves as a very suitable candidate to facilitate PSNs (Public Safety networks). PSNs are specifically planned networks to conduct search activities and rescue operations in case of the occurrence of any natural (flood, earthquake, etc) or man-made disaster (fire, war, etc). PSNs require the fastest communication mean to save the life and properties of people caught in trouble situation. Due to rapid and easy deployment, UAVs are emerging as the most suitable candidate for PSNs. UAVs are flying platforms without a human pilot. When a disaster happens it becomes difficult for humans to physically reach the scenes e.g., in case of fire, flood, or earthquake. Due to the pilot-less feature UAVs can actually reach the end-user at the actual disaster location which increases the efficiency of the rescue operation by many folds [19].

Future communication services such as video streaming, online gaming, and virtual reality require high data rate support [30]. To assist these future technologies the data rate needs to be increased in UAV-assisted HetNets so that these flying base stations can be equipped with high-speed communication equipment to provide better connectivity to ground users. Higher mobility of UAV BS requires a higher data rate to ensure a seamless handover between different base stations. UAVs can provide connectivity to multiple users simultaneously. However, to support multiple users, the data rate needs to be increased to prevent network congestion. UAVs can reduce the latency in communication networks by providing a direct line-of-sight connection between the user and the base station. Therefore, a higher data rate is required to support low latency communication [31]. Despite the large number of benefits offered by UAV-assisted communication some considerable problems and issues also exist that need to be addressed in order to maximize network efficiency. Among those challenges, the placement problem is a major one. In already existing terrestrial networks, the BS position is static and path loss completely relies upon the user's exact location with respect to that base station. In UAV assisted scenario the air-to-ground channel model between the end user and flying UAV depends on the actual position of the end user and the location of the UAV-assisted BS. UAV-assisted wireless base station deployment is a 3D placement scenario, which is different from terrestrial placement which is a 2D placement problem.

Furthermore, the resources like energy, bandwidth, power, time slot, etc are limited and shared. The energy resource used for operating the UAV onboard electronics is very scarce because onboard batteries are utilized as a power source and they have a limited lifetime. Therefore, UAVs are not capable of ensuring full coverage and only can offer fractional coverage. UAV deployment greatly impacts the coverage area, communication quality, and operating expenses. The limited resources (spectrum, onboard battery, power, etc are one of the key challenges in UAV-assisted HetNet operation. This work has considered the optimized resource allocation in UAV-assisted HetNet to maximize the network data rate subject to the constraints of power and QoS. Low complexity OAA is used to solve the MINLP problem of the proposed scenario.

The rest of the article comprises the following sections: section II includes the related work in detail. The system model has been presented in section III. Section IV includes problem formulation and a notation table. The proposed algorithm, its complexity, and convergence are discussed in section V. Simulations work and corresponding results are presented in section VI. Section VII comprises a Conclusion.

TABLE 1. Literature review: QoE-quality of experience. MINLP-mixed-integer non-linear programming.UAVs-unmanned aerial vehicles.QoS-quality of service.OAA-outer approximation.

Ref	Objective Function	Constraint	Problem Type	Algorithm	UM	SE	PM
1	Profit Maximization	Improved QOE, limited Backhaul capacity	MINLP	Novel Search	✓	✓	
2	minimize transmit power	coverage	Minimum coverage circle	Iterative ,exhaustive	✓		✓
3	minimized UAVs	Diff QOS requirement	convex	heuristic, Consecutive UAV deployment			
4	maximized covered users	Minimum power, Diff QOS	Multiple centric circle placement	Standard genetic, Multi population genetic.	✓		✓
5	Maximize covered users	Guaranteed Required data rate /user.	Knapsack problem (NP-complete)	Density aware 3D placement	✓		✓
6	Maximized discovered and covered users	Smaller elapsed time	Dynamic optimization, NP-hard	Particle Swarm Optimization	✓		
7	Maximized Network Coverage & Capacity	Minimized network entropy,	Decision, Network bargaining	Game theory	✓	✓	
8	Maximized Network Throughput	Mapping cost, energy, memory	optimization	Self-healing neural model, matrix coloring (backtracking)	✓	✓	
9	maximized users	minimum required transmit power	Circle placement problem, MINLP		✓	✓	✓
10	maximizing life-time of UAV network.	coverage radius		Disk covering model		✓	✓
11	minimized transmit power	path loss, coverage	Non convex	Particle Swarm Optimization	✓		✓
12	maximized number covered users	Diff QOS, Coverage radius	Multiple Circle placement , MINLP	.Exhaustive search	✓		
13	Minimized no of drones	Path loss, Communication radius, BW	NP-hard	Heuristic, Particle Swarm Optimization	✓		
14	Maximized Common Throughput	Aerial Station Energy Consumption	Non Convex	Closed Form ,convex Optimization	✓	✓	✓
15	Maximized no of Connected Devices	Network QoS, Battery Life, Budget	NP Hard	Heuristic	✓		
16	Maximized Network Throughput		MINL Convex	Two Layer Optimization, Iterative		✓	
17	Maximized Covered users	Power	MINLP	Heuristic	✓		✓
18	Maximized Indoor Coverage	Minimized Power	Non-Convex	iterative/Exhaustive	✓	✓	✓
19	This work	Power , rate	MINLP	OAA	✓	✓	✓

II. RELATED WORK

The three-dimensional BS placement and optimized resource allocation have been emerging research areas for a few years. The study in [1] has optimized the location of a single UAV-BS along with BW allocation to maximize the profit factor. It considers both the constraints of backhaul capacity and the price users are willing to pay for different required instantaneous data rates. In [2], the problem of power efficient optimal UAV deployment is considered, where the target is to minimize the required transmitted power for ensuring wireless coverage for users categorized as indoor users. The author in [3] has presented 3D UAV deployment to provide coverage to all users who have different QoS demands with a minimum number of UAVs involvement is presented. In [4] maximization of served users with variable Quality-of-Service (QoS) demand is presented while considering the minimum transmitted Power. The author in [5] has presented served users maximization problem. It has considered the minimum data rate requirement of each user as well. In [6] UAV trajectory planning based on the well-known Particle Swarm Optimization algorithm is presented, in which the Delay-Tolerant Networking approach is used. It has divided the task into two major steps, in the first step exploration of the disaster area is done, and in the second step, UAVs converge to various victim clusters discovered during the first step.

In [7] coverage improvement problem of UAV-assisted HetNet is presented. Demand area-based intelligent UAV deployment is considered. Above mentioned approach has resulted in the rise of network capacity and coverage. A self-healing neural model and matrix-coloring-based approach to place UAVs in such a manner to maximize throughput and user equipment (UE) to UAV mapping is proposed in [8]. Energy-efficient maximal coverage problem in UAV-assisted networks at the cost of the minimum transmitted power is considered in [9]. UAV placement problem is simplified by dividing it into two sub-problems (Horizontal placement and vertical placement problems). Work in [10] has considered optimized UAV placement problems while considering UAV-recall frequency as a major constraint. The objective is to make UAV -recall frequency as small as possible. A lifetime of a UAV-based network is represented by UAV recall frequency. Smaller the re-call frequency larger the lifetime of UAV based network. Work in [11] has considered a scenario in which there is some kind of disaster has occurred and users who need communication are distributed in an even manner on each floor, inside a high-rise building. A particle swarm optimization-based approach is presented for optimized UAV placement. Placement is done while considering power constraints. The purpose is to minimize the total required transmitted power for coverage. The authors in [4] have considered a scenario in which user demand varies in terms of QoS requirements. It has presented a novel solution to maximize the covered users demanding different Quality-of-Service.

A low-complexity, the maximal weighted area (MWA) algorithm is presented to tackle the coverage problem. In [12] author has presented a situation of uneven terrain and the objective is to optimally place drones in such kind of situation while maintaining the coverage and connectivity demands of end-users. Particle swarm optimization algorithm-based heuristic is presented to obtain an optimized solution in terms of cost. In [13] common throughput maximization for both (Time Division Multiple Access) TDMA and FDMA (Frequency Division Multiple Access) resource-sharing schemes is achieved by joint optimization of resource allocation and BS placement. UAV placement with minimized power and maximized covered users is presented in [9]. The 3D placement is simplified by decomposing it into two sub-problems 1) horizontal and 2) vertical placement problems. A 2D circle placement problem-based approach is used for horizontal direction and for vertical direction elevation angle optimization approach is used to achieve the optimized altitude. In case of disaster, information about the communication path whether it will be LoS or NLoS is usually missing. Work in [9] has considered averaged path loss model. 3D UAV placement for indoor users with minimized transmitted power is discussed in [2]. It has considered two placement optimization cases. In the first case, it has considered the position inside a building that is offering the highest path loss factor. In the second case, building users are assumed to be distributed in a uniform manner inside the building and the exhaustive algorithm is used for placement optimization. Multiple UAV 3D placement in the existence of interference (co-channel) is discussed in [21].

Authors in [22] have considered the UAV relay placement problem. Resource allocation scheme for Terahertz (THz) unmanned aerial vehicles (UAVs)-based heterogeneous networks (HetNets) is presented in [27]. The proposed scheme employs a joint optimization framework that takes into account the channel state information (CSI), the quality of service (QoS) requirements of the different user types, and the power consumption of the UAVs. The scheme also considers the mobility of the UAVs and the interference caused by the nearby UAVs and ground nodes. The work in [28] presents a resource management scheme for the unmanned aerial vehicle (UAV)-assisted re-configurable intelligent surface (RIS) heterogeneous networks (HetNets) supported by dual connectivity. The goal is to minimize the transmit power of the base station (BS) while satisfying the quality-of-service (QoS) requirements of the users. The work in [29] has discussed efficient resource allocation strategies for fifth-generation (5G) and beyond networks that use hybrid non-orthogonal multiple access (NOMA) techniques in heterogeneous environments. The proposed strategy aims to optimize the allocation of radio resources and achieve a balance between the Quality of Service (QoS) requirements of users, fairness among users, and energy efficiency in the network. A comparison of Reference papers is given in Table 1.

The key challenges addressed in this paper are optimized resource allocation for data rate maximization of UAV-assisted HetNet subject to the constraints of power and QoS using low complexity OAA. To the best of our knowledge, this work has not been considered before. The major contribution of this research work are:

- This work has proposed a mathematical framework for UAV-based heterogeneous networks given in Fig 1.
- Low complexity heuristic is proposed for data rate maximization of UAV-assisted heterogeneous network

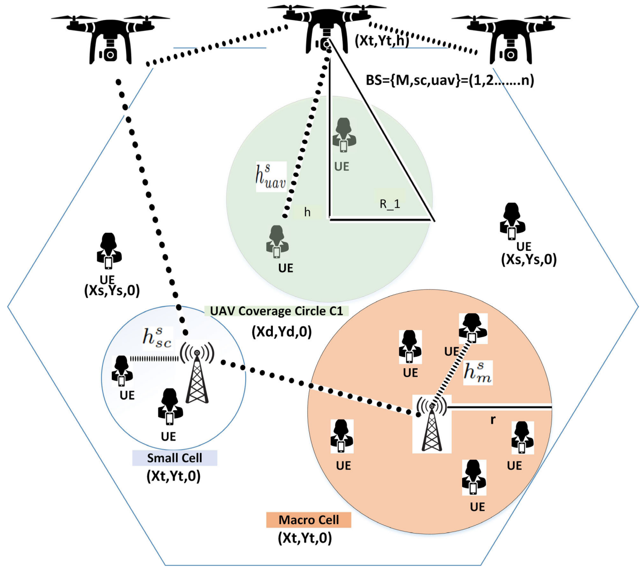

FIGURE 1. UAV assisted HetNet.

- Simulation work is performed to compare the data rate performance of UAV-assisted HetNet with Macro only scenario.
- UAV-assisted HetNet is investigated for different QoS criteria via simulation work.
- Comparison of supported users for UAV-assisted HetNet and macro-only scenario is performed via simulations.
- UAV-assisted HetNet-supported users are investigated at variable data rates.
- Performance of the proposed algorithm is verified by comparison with other state-of-the-art techniques and its outperformance is proved via extensive simulation work.

III. SYSTEM MODEL

Heterogeneous Network is a type of wireless network architecture that combines different types of access nodes to provide improved coverage and capacity for mobile devices. This article considers UAV-assisted HetNet, having macro cells, small cells, UAV-mounted base station, and user equipment (UE) as shown in Fig 1. It is supposed that macro eNB is covering a radius r. UAVs are present at a hovering altitude of h which is a minimum value of altitude to overcome ground obstacles. UAVs can be placed anywhere to cover as many users as possible with the optimized network throughput. Each user will be provided communication services either by small cell(sc), macro cell(m), or UAV-mounted BS. Let S be the total number of users that need to communicate with each other and T is a subset of available BS where $t \in T$ and $T = \{m, sc, uav\}$. Let z^s_t be a binary indicator representing that by which BS among macro eNB, small eNB, or UAV eNB, user s is connected. Power received in downlink by the user s from BS t is denoted by p^s_t where $t \in T$. The channel between s^{th} user and BS t is h^s_t. The antenna gain value is denoted by G_o and $\zeta 10^{\zeta/2}$ represents a zero-mean

Gaussian random variable that has a standard deviation value of σ. The communication channel gain value [34] is modeled as:

$$.h_t^s = \overline{h_t^s}\zeta G_o(do/d)^{\alpha} \tag{1}$$

$\zeta G_o(do/d)^{\alpha}$ represents the path loss component of the channel gain equation, where the distance value between transmitter and receiver is represented by d, the reference distance of antenna far-field is d_o, α represents path loss exponent value. $\overline{h_t^s}$ is the expression for the Rayleigh random variable that models the amplitude of a signal that has undergone Rayleigh fading, which is a type of fading that occurs in wireless communication due to multipath propagation.

Interference experienced by user s when connected with BS t can be written as 1) reception by user s from BS t' is DL $\hookrightarrow$ DL interference. In this particular case, SINR can be written as:

$$SINR_{t,t'}^s = \frac{(p_t^s h_t^s)}{\sum_{t' \in T, t' \neq t}(p_{t'} h_{t'}^s) + N_o}, \quad \forall t \in T, \forall s \in S \tag{2}$$

2) reception by user s from user s' is UL $\hookrightarrow$ DL interference and can be written as:

$$SINR_{t,s'}^s = \frac{(p_t^s h_t^s)}{\sum_{s' \in S, s' \neq s}(p_{s'} h_{s'}^s) + N_o}, \quad \forall t \in T, \forall s \in S \tag{3}$$

The spectral efficiency of s^{th} user at base station t is given below:

$$c_t^s = log_2(1 + SINR_t^s) \tag{4}$$

N_o is white Gaussian noise power. User s can make connection to only one BS at a time, it can be macro eNB, small eNB, or UAV eNB. $z_t^s \in \{0, 1\} \vee t \in T, s \in S$ and $S = \{1, 2, 3..\}$.

Several Air to Ground (ATG) channel models have been presented in previous research for UAV BS communication. However, this work has considered the ATG channel model presented in [9] and [26]. According to it signals emitted by a low altitude platform, UAV in our scenario, reach the urban environment after experiencing free space path loss (FSPL) along with the additional losses e.g., scattering and shadowing caused by man-made structures. Due to the presence of man-made structures in urban environments signals from UAV to ground users can be from both (line of sight) LoS and (Non-line of sight) NLoS groups. The probability of having a LoS link between user s and a UAV BS can be written as:

$$P_{LoS} = 1/1 + a\exp(-b(180/\pi)\tan^{-1}(h/r_s) - a)) \tag{5}$$

where a and b are environmental constants known as "S-curve parameters" and are given in [26]. r_s is the distance between the user s and UAV coordinates on the horizontal plane and is given by the expression:

$$r_s = \sqrt{((x_s - x_d)^2 + (y_s - y_d)^2)} \tag{6}$$

TABLE 2. Notations table.

Defination	Symbol
UAV coverage circle c1 radius	R_1
Macro eNB radius	r
UAV's hovering altitude	h
Total no of users	S
User s is connected to t BS	z_t^s
Power received by user s connected to BS t	p_t^s
Data rate allocated to user s connected to BS t	d_t^s
Channel gain between the sth user and BS t	h_t^s
Subset of Base stations	T
Antenna Gain	G_0
Zero mean Gaussian Random Variable	ζ
Log normal Shadowing	$\zeta 10^{\zeta/2}$
Standard Deviation	σ
Channel capacity allocated to Sth user on base station t	c_t^s

where(x_s, y_s) and (x_d, y_d) show the coordinates of the user s and UAV coverage disk respectively, and h is UAV hovering altitude. The probability of having a NLoS link between users and UAV is as follows [26].

$$P_{NLoS} = 1 - P_{LoS} \tag{7}$$

Due to the urban environment both LoS and NLoS channels experience additional losses along with the free space path loss. Work in [9] and [26] have considered mean path loss for long-term planning while ignoring the small-scale fluctuations. Path loss expressions [9] for both LoS and NLos are as follows:

$$L_{LoS} = 20log((4\pi f_c d_s)/c) + \eta_{LoS} \tag{8}$$
$$L_{NLoS} = 20log((4\pi f_c d_s)/c) + \eta_{NLoS} \tag{9}$$

wheref_c is the carrier frequency and d_s is the distance between user s and UAV BS given by the expression:

$$d_s = \sqrt{h^2 + r_s{}^2} \tag{10}$$

η_{LoS} and η_{NLoS} are mean additional losses due to scattering and shadowing phenomena of the urban environment in both LoS and NLoS channels and are explained in [26].

This research work has focused on maximizing network data rates. Optimized resource allocation is performed for UAV-assisted HetNet to get an overall optimized solution in terms of network data rate and users connected subject to the power and QoS constraints.

IV. PROBLEM FORMULATION

We considered a Cartesian coordinate system in which the location of base station t, $t \in T, T = \{m, sc, uav\}$ and user s is given by$\{x_t, y_t, z_t\}$, $\{x_s, y_s, 0\}$. $Z_t = h$ for UAV eNB and 0 for Macro and Micro eNB. Optimized UAV placement means optimizing vertical placement (UAV altitude) and horizontal placement (coverage disk). According to [26] if the coverage region is plotted against UAV height, then at one particular stationary point maximum value for the coverage region exists for any specific QoS criteria. Numerically optimized altitude [9] to achieve maximized coverage can be calculated by the following expression.

$$h = R_1 tan(\theta_{opt}) \tag{11}$$

where (θ_{opt}) and R_1 are numerically calculated. The horizontal coverage region of UAV-BS is assumed to be a circular disc. Horizontal optimized UAV placement means optimally placing a circular disc on the horizontal plane. If c1 is representing the coverage region with radius R_1. Now, we need to optimally center the coverage region c1 on the horizontal plane such that it improves coverage and overall network throughput of UAV-assisted HetNet. (x_d, y_d) shows the coordinates of the UAV coverage disk. This can be written as shown in the equation written below [9].

$$z^s((x_s - x_d)^2 + (y_s - y_d)^2) \leq R_1^2 \tag{12}$$

where z^s is a binary indicator. if $z^s = 1$ shows that user s is in the UAV coverage region otherwise not. To impose the demands of the above-mentioned condition in case $z^s = 0$ this condition can be rewritten as

$$(x_s - x_d)^2 + (y_s - y_d)^2 \leq R_1^2 + M(1 - z^s) \tag{13}$$

where the M value is representing a large constant. Power is another major constraint so our optimization problem requires that the sum of power allocated to all users connected to a BS must be less than or equal to total BS power. The data rate allocated to each user must be greater than the minimum required data rate to be inside the BS coverage area. z_t^s is a binary indicator that shows that either user s is connected with base station t or not.

$$z_t^s \in \{0, 1\}, \forall t \in T, \forall s \in S \tag{14}$$

Each user must be connected to a maximum of one base station at a time according to constraint C2. Each user is allocated a certain amount of power from base station t if its binary indicator z_t^s which shows its connectivity with base station t is 1 otherwise no power allocation to the user s from base station t. According to constraint, 6 power allocated to users connected with base station t must be larger than zero. Combine UAV placement and Network throughput maximization problem can be written as

$$\begin{aligned}
&\max_{p,z} \sum_{t \in T} \sum_{s \in S} c_t^s z_t^s \\
&\text{Subject to: } C1 : ((x_s - x_d)^2 + (y_s - y_d)^2) \leq R_1^2 + M(1 - z_t^s) \\
&\qquad C2 : \sum_{t \in T} z_t^s \leq 1 \quad \forall s \in S \\
&\qquad C3 : \sum_{s \in S} p_m^s \leq P_m, \\
&\qquad C4 : \sum_{s \in S} p_{sc}^s \leq P_{sc}, \\
&\qquad C5 : \sum_{s \in S} p_{uav}^s \leq P_{uav}, \\
&\qquad C6 : p_t^s \leq z_t^s P_t, \quad \forall t \in T, \ \forall s \in S \\
&\qquad C7 : c_t^s z_t^s \geq D \\
&\qquad C8 : p_t^s \geq 0, \quad \forall t \in T, \ \forall s \in S
\end{aligned} \tag{15}$$

Algorithm 1 :Outer Approximation Algorithm

$\upsilon \leftarrow 1$
Initialize χ
$\varepsilon \leftarrow 10^{-3}$
Convergence $\leftarrow$ *FALSE*
while *Convergence* == *FALSE* **do**
  $\rho^{\upsilon} \leftarrow \begin{cases} \arg\min_{\mathcal{P}} \; -K(\chi, \rho) \\ \text{subject to } \phi_{c1-c8}(\chi, \rho) \leq 0; \end{cases}$
  UpperBound $\leftarrow K(\chi^{\upsilon}, \rho^{*})$
  $(\chi^{*}, \rho^{*}, \varphi^{*}) \leftarrow \begin{cases} \arg\min_{\chi,\rho,\varphi} \varphi \\ \text{subject to} \\ \varphi \geq -K(\chi^{\upsilon}, \rho^{\upsilon}) \\ -\nabla K(\chi^{\upsilon}, \rho^{\upsilon}) \binom{\rho-\rho^{\upsilon}}{0} \\ \phi_{c1-c8}(\chi^{\upsilon}, \rho^{\upsilon}) \\ -\nabla \phi_{c1-c8}(\chi^{\upsilon}, \rho^{\upsilon}) \binom{\rho-\rho^{\upsilon}}{0} \leq 0 \end{cases}$
  LowerBound $\leftarrow \varphi$
  if UpperBound − LowerBound $\leq \varepsilon$ **then**
    Convergence $\leftarrow$ *TRUE*
  else
    $\upsilon \leftarrow \upsilon + 1$
    $\chi^{\upsilon} \leftarrow \chi^{*}$
  end if
end while

where c_t^s is the data rate allocated to user s connected with base station t. User serving is defined in terms of satisfaction with minimum required QoS criteria. According to C1, the user s is served by UAV if it is situated at a location that is within distance R1 from the center of the coverage region c1 [9]. C2 indicates that each user must be connected with not more than one base station at a time. C3 to C5 indicate that power allocated to all users connected with one of the BS must be less than the total power of the corresponding BS. C6 indicates that power allocated to any user connected to a BS must be less than the total power of that BS and must be zero when not connected with that BS. C7 and C8 indicate the minimum data rate and power requirement for any user.

Problem formulation indicates that it is an MINLP problem that is difficult to solve due to its NP-hard nature. Exhaustive search is one of the methods to solve such kinds of NP-hard problems but it is not a suitable solution due to its complexity as the search space of exhaustive search increases in an exponential manner with the number of users. An outer approximation is one of the algorithms to solve NP-hard problems with limited complexity. The proposed algorithm is evaluated with help of simulations and has shown outperformance in terms of total communicating network throughput value.

V. PROPOSED ALGORITHM

The OAA-based algorithm [35] is presented to provide a solution for the throughput and coverage problem of UAV-assisted HetNet.The pseudo-code is given in algorithm 1.

The proposed problem in equation 15 is a complex MINLP due to the presence of NL objective function, NL constraints, and mixed-integer nature of variables e.g., continuous (Power), integer(users admitted), and binary z_t^s, z^s. NP-hardness of the proposed problem increases continuously with the increase in the number of users demanding both coverage and data rate. Therefore exhaustive search cannot serve the purpose. This work has proposed an Outer Approximation (OAA) based ϵ optimal algorithm to proposed MINLP. OAA works on the principle of branch and bound in which the original problem is decomposed into two types of problems one is a nonlinear subproblem (NLP) which is a primary problem and the other one is a mixed integer linear problem (MILP) which is a master problem. In the first iteration, the new NLP subproblem is solved with the binary initial value (in the 0–1 integer model) and mixed-integer value of a variable (in the mixed-integer model). Its feasible solution represents an upper bound. Linearization is added to the nonlinear objective function and nonlinear constraints to obtain master MILP. As the master problem is actually a relaxed form of the original MINLP hence it provides a lower bound value of the required solution. Comparison of the upper and lower bound decides whether we have reached the desired solution or not. if not then a new iteration is performed with the new value of variables. Let's denote the objective function by symbol K and constraints C1 to C8 by ϕ_{C1-C8}. $\rho = \{\rho_m, \rho_{sc}, \rho_{uav}\}$ is a set of continuous variables representing macro, small cell UAV powers respectively and $\chi = x \cup \rho$ is represented as discrete variables. Equation (15) can easily be verified for the following hypothesis.

1) ρ satisfies convex, compact, and non-empty behavior. K and ϕ_{C1-C8} are also convex in ρ for fixed values of χ.
2) K and ϕ_{C1-C8} are once continually differentiable.
3) Nonlinear continuous sub-problem solution attained by setting the value of χ holds constraint qualification.
4) Obtained NLP can be solved exactly by fixing χ values.

As already stated problem in equation 15 is a representation of MINLP class for which an exhaustive search is not a suitable solution. This kind of problem can be solved by Branch and Bound based OAA which generates non-decreasing lower and non-increasing upper bounds for the above-mentioned MINLP. The main problem is distributed into primal and master problems to achieve the Lower and upper bounds. The primal problem is determined by setting χ values. Let at υ^{th} iteration of OAA integer variable value is χ^{υ}. The primal problem can be written as

$$\min_{\rho} -K(\chi^{\upsilon}, \rho) \tag{16}$$

$$\text{Subject to: } \phi_{c1-c8}(\chi^{\upsilon}, \rho) \leq 0 \tag{17}$$

Solving the primal problem gives the value of ρ^{υ}'which is then used in the master problem. The Upper bound is the resultant of the primal problem solution and the master problem solution provides a lower bound. OAA is applied on objective function K and $C_1 - C_8$ to derive the master problem. The integer variable $\chi^{\upsilon+1}$ is generated as a solution to the master problem that is used in the next iteration. Iterations remain to continue until the difference value among both upper and lower bounds is less than ϵ The problem in (15) can be rewritten as

$$\min_{\chi}\min_{\rho} -K(\chi^{\upsilon}, \rho) \tag{18}$$

$$\text{Subject to: } \phi_{c1-c8}(\chi^{\upsilon}, \rho) \leq 0 \tag{19}$$

Projection of the problem proposed in (6) in χ can be rewritten as:

$$\min_{\chi} -\varphi(x) \tag{20}$$

where

$$\varphi(x) = \min_{\rho} -K(\chi^{\upsilon}, \rho) \tag{21}$$

$$\text{Subject to:} \phi_{c1-c8}(\chi^{\upsilon}, \rho) \leq 0 \tag{22}$$

such projection problems are solved as follows:

$$\min_{\chi}\min_{\rho} -K(\chi^{\upsilon}, \rho^{\upsilon}) - \nabla K(\chi^{\upsilon}, \rho^{\upsilon}) \begin{bmatrix} \rho - \rho^{\upsilon} \\ \chi - \chi^{\upsilon} \end{bmatrix} \tag{23}$$

$$\text{Subject to: } \phi_{c1-c8}(\chi^{\upsilon}, \rho^{\upsilon}) - \nabla \phi_{c1-c8}(\chi^{\upsilon}, \rho^{\upsilon}) \begin{bmatrix} \rho - \rho^{\upsilon} \\ \chi - \chi^{\upsilon} \end{bmatrix} \leq 0 \tag{24}$$

The new variable φ leads to an equivalent minimization problem as follows:

$$\min_{\chi,\rho,\varphi} \varphi \tag{25}$$

$$\varphi \geq -K(\chi^{\upsilon}, \rho^{\upsilon}) - \nabla K(\chi^{\upsilon}, \rho^{\upsilon}) \begin{bmatrix} \rho - \rho^{\upsilon} \\ \chi - \chi^{\upsilon} \end{bmatrix} \tag{26}$$

$$\phi_{c1-c8}(\chi^{\upsilon}, \rho^{\upsilon}) - \nabla \phi_{c1-c8}(\chi^{\upsilon}, \rho^{\upsilon}) \begin{bmatrix} \rho - \rho^{\upsilon} \\ \chi - \chi^{\upsilon} \end{bmatrix} \leq 0 \tag{27}$$

Lower bounds are found in (26).

A. COMPLEXITY OF ALGORITHM

The complexity of an algorithm depends upon the number of flops present in an algorithm. Flop is a real floating point operation in the proposed algorithm [23]. Each real division, multiplication, and addition in algorithm execution contributes one flop. Complex addition two and complex multiplication contribute four flops in the complexity of the algorithm. The scenario of the addition of an element or its removal from the algorithm contributes one flop. a x b matrix multiplication with a matrix of b x c dimensions results in the addition of 2abc flops. Any assignment or logical operator contributes one flop.

In the proposed algorithm one flop each is contributed by steps 1-5. Statement 6 which consists of a while loop is contributing 2XY flops where X is the number of users and Y is the total number of RRHs. 4XYB flops are contributed by statements 7 and 8 each of the proposed algorithm, where

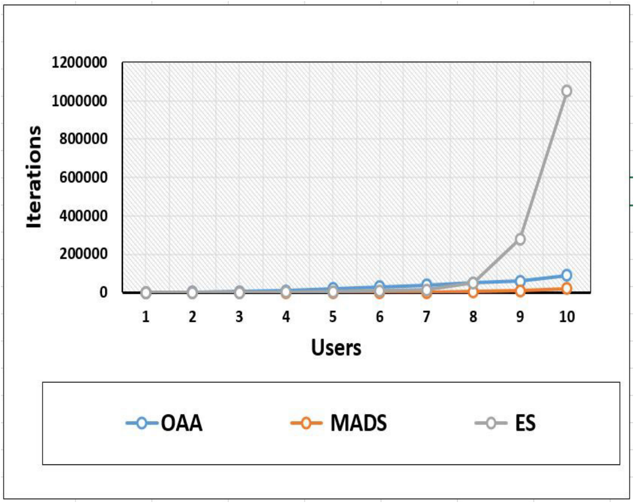

FIGURE 2. Complexity Comparison.

B is the constraint count of each user. Statement 9 is offering 2NZB flops. 2 flops by statement 10, 1 from statement 11, and 2 from statement 13 are contributed. The total flop count of the proposed algorithm is as follows:

$$F_{OAA} = 5 + 2XY + 4XYB + 4XYB + 2XYB + 1 + 2 + 1 \quad (28)$$

$$F_{OAA} = 2XY + 10XYB \quad (29)$$

The Exhaustive search algorithm is computationally complex as it requires evaluating the objective function at every possible combination of decision variables. This results in a complexity that grows exponentially with the number of users, represented as S, and can be expressed as $com = 2^{2S}$ where com is representing complexity. On the other hand, the complexity of the OAA algorithm is moderate when compared to the exhaustive search (ESA), as it involves solving a series of linear programming problems. The complexity of the OAA algorithm can be represented as Com=$(S^2 f)/e$, where f is the number of constraints and e is the error tolerance. OAA algorithm has a complexity that is a multiple of the number of constraints when compared to the MADS algorithm [33]. A complexity comparison of OAA, ESA, and MADS is given in Figure 2, [32]. The low complexity of the proposed OAA as compared to ESA makes it a viable solution for data rate maximization of UAV-assisted HetNets.

B. CONVERGENCE OF ALGORITHM

According to [24] OAA converges linearly. The proposed OAA-based resource allocation algorithm for UAV-assisted HetNet gives optimized results for $\varepsilon = 10^{-3}$ in the finite number of iterations only if both constraints and objective function are convex in nature and variable χ is finite [25]. In statement 8 of proposed algorithm $\varphi \geq K(\chi^{\upsilon}, \rho^{\upsilon})$ ensures the optimality of ρ. If not the case then it means no feasible solution and it is removed from the master problem. It leads to the convergence of the proposed algorithm.

TABLE 3. Parameter table.

Parameter	Value
Data Rates	[0.25.1,3]Mbps
r	1000m
P_m	[8 2]
P_S	4
P_U	8
α	2
G_0	50
Min Users	2
Maximum User	40
Use Increment	2
ζ	10dB

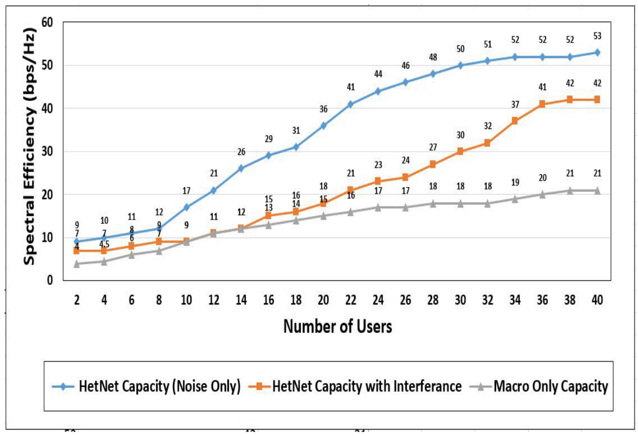

FIGURE 3. Spectral Efficiency Vs number of users (For each user f = 1MHz orthogonal band is used and hence Data rate = f× Spectral Efficiency).

VI. RESULTS

In the following section, extensive simulation results are discussed to prove the efficiency of the proposed OAA (BONIM) based Non-Linear algorithm that is used to solve the problem presented in equation 15. Table 3 shows the parameters used in the simulation process. Through simulations, results have shown the outperformance of the proposed algorithm to solve the MINLP presented in equation 15.

In Figure 3 UAV assisted HetNet data rate analysis is presented with an increasing number of users and a comparison is made between UAV-assisted HetNet and Macro-only scenarios. For each user, f = 1MHz orthogonal band is used, and hence data rate = f × Spectral Efficiency. Figure 3 also shows a comparison between the UAV-assisted spectral efficiency for the case when only noise is present and the case when both noise and interference are considered. Simulation is performed for a maximum of 40 users. Results show that the HetNet case data rate is much higher than the macro-only case. With an increasing number of users, the data rate has also shown an increasing trend with a maximum of 53Mbps for HetNet and 22Mbps for Macro only for 40 users. Figure 3 has also presented a comparison

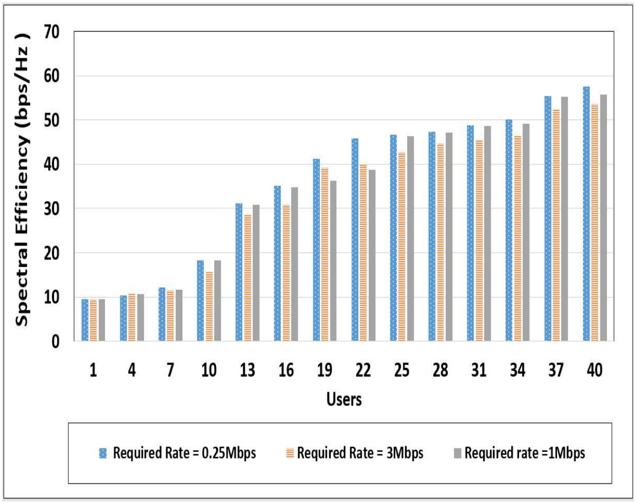

FIGURE 4. Spectral Efficiency for different data rates.

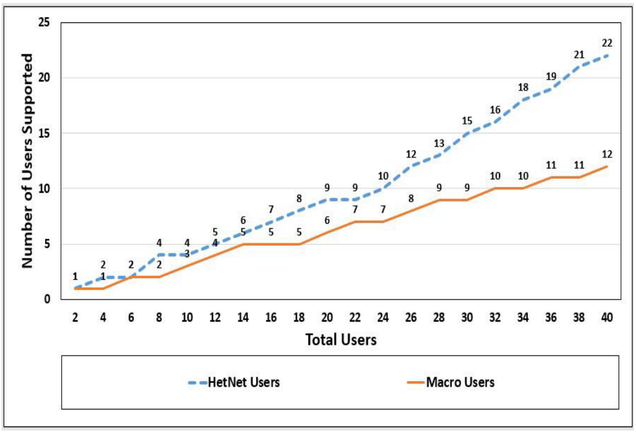

FIGURE 5. Hetnet selected users.

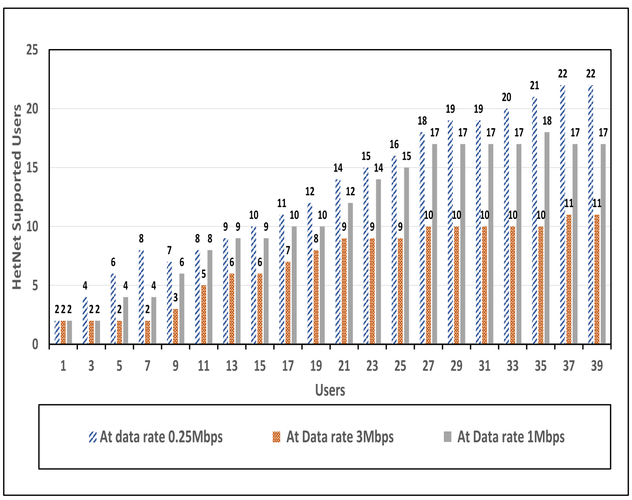

FIGURE 6. HetNet associated users for different data rates.

between UAV-assisted HetNet data rate in case of interference with Macro-only data rate with an increasing number of

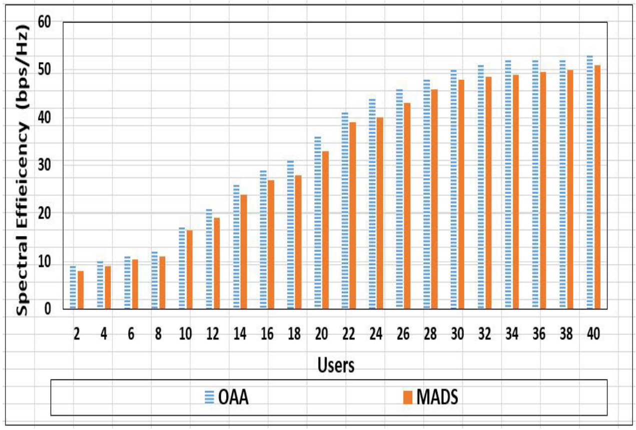

FIGURE 7. Comparison between proposed algorithm and MADS.

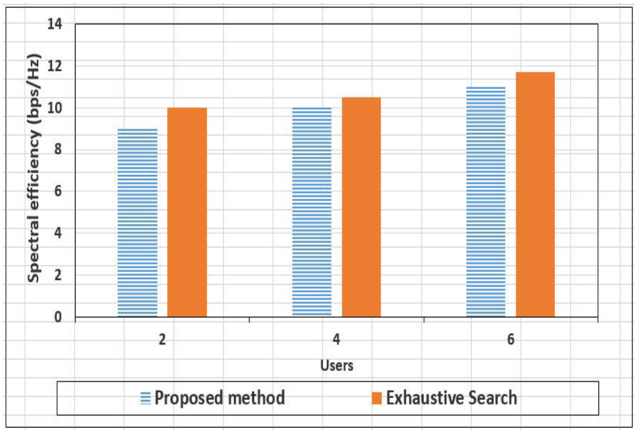

FIGURE 8. Comparison between proposed Algorithm and Exhaustive Search Algorithm.

users. Results have clearly indicated the outperformance of UAV-assisted HetNet even in the presence of interference with a maximum of achieved 42Mbps data rate that is much higher as compared to the macro-only data rate.

Simulation work has considered UAV-assisted HetNet data rate comparison with different required data rates. Figure 4 shows the HetNet data rate for 3 different data rates [3, 0.25, 1] Mbps with an increasing no of users. Results show that as the number of users is increasing data rate is still increasing for the HetNet scenario with the varying QoS requirement as well. Figure 5 has analyzed associated users with both Macro only and UAV-assisted HetNet scenarios. Results show that users associated with HetNet are considerably higher as compared to Macro network and the same trend is maintained even with an increasing number of users.

Figure 6 has analyzed HetNet-associated users for three different data rates [3, 0.25, 1] Mbps. HetNet-associated users are continuously increasing even at different rates as well. However, a decreasing trend in associated users is observed with an increasing data rate. The highest associated users are recorded at 0.25Mbps.

Figure 7 compares UAV-assisted HetNet data rate using two different algorithms OAA and MADS [33]. We have used NOMADS (Nonlinear optimization using MADS) for simulation purposes. The result has proved the outperformance of OAA as compared to MADS. Figure 8 shows a comparison between the proposed OAA-based heuristic method with ESA. ESA presents slightly better results in comparison to the proposed algorithm but at the cost of extremely high computational complexity as evident from Figure 2 and Figure 8. Therefore, the comparison is only performed for up to 6 users. Further, an increase in the number of users increases the computational complexity of ESA up to many folds, which makes it a non-feasible solution.

VII. CONCLUSION

This paper addresses the efficient resource allocation problem for UAV-assisted heterogeneous networks to maximize the network data rate subject to the constraints of power and QoS. The OAA-based algorithm is proposed to solve the formulated MINLP resource allocation problem and to achieve $\varepsilon = 10^{-3}$ optimal solution. ε optimal results are achieved for the UAV-assisted HetNet resource allocation problem. Results indicate that the proposed OAA-based novel resource allocation algorithm for UAV-assisted heterogeneous network outperforms homogeneous (Macro only) networks in terms of network throughput and connected devices. Results are verified by increasing the number of total users up to 40. Simulations are also performed for different data rate requirements(0.25,1,3)Mbps. Results have shown that the proposed algorithm performs better regarding network throughput and associated users even with variable required QoS requirements. However, a decrease in network throughput and user association is observed with an increasing required data rate. The proposed algorithm is also compared with other state-of-the-art methods (MADS and ESA) to verify its outperformance.

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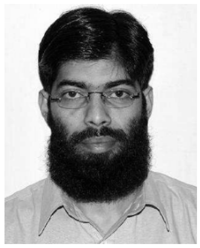

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