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Joint DL/UL Decouple User Association in Microwave and mmWave Enabled Beyond 5G Heterogeneous Networks

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ABSTRACT Beyond fifth-generation (5G) heterogeneous networks (HetNets) are facing the challenge of accommodating enormous mobile users and data traffic with scarce spectrum resources in the microWave (μWave) band. In this work, we consider both challenges in HetNets comprising large size, high power base station (LHB) and relay operating in μWave band and small size, low power base station (SLB) and device-to-device (D2D) operating in millimeter wave (mmWave) band. We formulate user association optimization problems to pitch user association schemes based on downlink uplink decoupled (DU-DPL) access against traditional downlink uplink coupled (DU-CPL) access in HetNets to gauge the performance of these access schemes in terms of accommodating users and spectrum efficiency in μWave and mmWave bands. Formulated problems are non-deterministic polynomial-time hard (NP-hard) and solved using ϵ-optimal algorithm. Simulation results show the edge of DU-DPL access over DU-CPL access in terms of users association and spectrum efficiency.

INDEX TERMS User association, mmWave, spectrum efficiency, MINLP, heterogeneous networks.

I. INTRODUCTION

Mobile devices and monthly mobile data traffic will grow to 12.3 billion and 77 exabytes, respectively, in 2022 [1]. Forecasted exponential growth in mobile users viz-a-viz data traffic is a result of data-hungry applications i.e., video calls, machine-to-machine communication, social networking services, and real-time video gaming, etc [2]. Fifth-generation (5G) and beyond heterogeneous networks (HetNets) comprising large size high power base stations (LHB) along with small size low power base stations (SLB), relays station, and device-to-device (D2D) communication need to accommodate this explosive growth in mobile users and data traffic in the coming days.

In past, HetNets comprising LHB along with SLB, relay, and D2D communication has played a pivotal role to accommodate more users, enhance throughput, capacity and seamless coverage [3]. Relay along with D2D communication augment coverage and capacity in HetNets [4], [5]. Here, user association was based on the downlink (DL) and uplink (UL) coupled (DU-CPL) where strongest receive signal power (SRP) in the DL only [6] dictates user association with a base station (BS). However, transmit power disparity among HetNets nodes [7] compel the majority of the users to associate with LHB and the minority of users associates with SLB making spectrum resources underutilized. Thus, DU-CPL access is not an optimal solution for user association beyond 5G HetNets. The solution to this challenge is DL-UL decouple access (DU-DPL) where a user associates with a BS basing on SRP in the DL and weakest path loss (WPL) in the UL [8]–[10]. Thus, the freedom offered by DU-DPL access to a user for association in the DL and UL, independently, reduces user-BS distance, SLB spectrum resources are utilized efficiently and network capacity is maximized significantly.

On another side, the demand and supply gap of traditional spectrum resources in the microwave (μWave) band has reached its bottleneck. Spectrum resources in millimeter wave (mmWave) band are envisaged to meet explosive spectrum demand in 5G and beyond HetNets [28], [29].

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TABLE 1. Review of Literature:UA-User Association, TM-Throughput Maximization, EE-Energy Efficiency, SE-Spectral Efficiency, UAM-User Association Maximization, RBM-Resource Block Minimization, UAV-unmanned aerial vehicle, mmWave-millimeter Wave Band, μWave-Micro Wave Band, TO-Traffic Offloading, MMSE-Minimum Mean Square Error

Ref	Research objective	DU-CPL	DU-DPL	UAM	RBM	μWave	mmWave	LHB, SLB	Relay	D2D	TO in DL	TO in UL	Algorithm/Technique
[11]	UAM			✓		✓	✓	✓					Heuristic user association algorithm
[12]	UAM, RBM			✓	✓	✓	✓	✓			TO to SLB		Heuristic user association algorithm
[13]	UAM, RBM			✓	✓	✓		✓					user-to-BS association algorithms
[14]	UA, EE					✓	✓	✓			TO to SLB		Lagrangian dual decomposition method
[15]	UA, TM					✓	✓	✓			TO to SLB		Two stage QoS greedy pair algorithm
[16]	UA, TM, EE						✓	✓			TO to SLB		Heuristic algorithm
[17]	UA, EE						✓	✓					Non-dominated sorting genetic algorithm
[18]	UA, EE					✓	✓	✓					User-centric scheme
[19]	UA, TM, EE		✓				✓	✓			TO to SLB	TO to SLB	Capacity-based cell association schemes
[20]	UA, EE		✓			✓	✓	✓			TO to SLB	TO to SLB	Generalized assignment problem heuristic
[21]	UA, SE		✓			✓	✓	✓			TO to SLB	TO to SLB	Stochastic geometry
[22]	UA, TM		✓					✓			TO to SLB	TO to SLB	Decoupled generalized user association scheme
[23]	UA, TM		✓					✓			TO to SLB	TO to SLB	Swap matching algorithm
[24]	TM		✓					✓			TO to SLB	TO to SLB	Data aided MMSE scheme
[25]	UA, TM	✓	✓					✓	✓	✓	TO to SLB, relay, D2D	TO to SLB, relay, D2D	Outer approximation and heuristic algorithm
[26]	UA, TM	✓	✓			✓		✓		✓	TO to SLB, D2D	TO to SLB, D2D	modified Munkres algorithm
[27]	UA, EE	✓	✓			✓		✓			TO to SLB, UAV	TO to SLB, UAV	Q-Learning power allocation schemes
This work	UAM, TM, RBM	✓	✓	✓	✓	✓	✓	✓	✓	✓	TO to SLB, relay, D2D	TO to SLB, relay, D2D	ϵ-optimal algorithm

Higher penetration losses make mmWave communication un-feasible for future cellular networks. However, beamforming and directional antennas techniques can be effective in handling this challenge [30]–[32]. Thus, DU-DPL access enabled hybrid HetNets operating in μWave and mmWave band is an attractive proposal to address the challenges like accommodating mobile users with data-hungry services and scarce spectrum resources in (μWave) band for beyond 5G HetNets.

A. LITERATURE REVIEW

The authors in [11] investigate user association maximization (UAM) in μWave and mmWave band using orthogonal multiple access and non-orthogonal multiple access techniques in homogeneous networks. The study in [12], [13] investigates UAM and resource block minimization (RBM) problem to ensure efficient resource utilization in the DL only using μWave and mmWave in HetNets. These studies show that user association increases with an increase in the number of sub-channels and decreases with an increase in minimum data rate requirements in HetNets.

DU-DPL access application in μWave-mmWave hybrid HetNets has been studied by several studies. The approach in [14] investigates jointly user association and power allocation problems while considering QoS requirements, interference, energy harvesting, and energy efficiency in mmWave based HetNets. Results show that user association and user rate based on load-balancing improves network EE significantly. The recent work in [15] proposes a two-stage algorithm for user association and resource allocation using and μWave and mmWave band to maximize throughput in HetNets. Proposed algorithms reduce interference, improves spectrum utilization, and improve system capacity. More recently in [16] investigates power control and scheduling to maximize capacity and energy efficiency using a heuristic algorithm. Recent work in [17] Optimize user association and power allocation for a trade-off between EE and fairness in multi-connectable mmWave networks. The results in [18] show that hierarchical SDN architecture considering dynamic subordinate SDN management and mobility management performs

better in terms of balance load and EE.

Authors in [19] investigate DU-DPL access in a multi-association case where the user can associate with multiple BSs. This study shows that DU-DPL access achieves several times higher EE and data rates than traditional DU-CPL access using mmWave and UHF band in HetNets. A recent study in [20] explores multi-connectivity user association problems in heterogeneous Cloud Radio Access Networks. The results show that an increase in the number of cooperating BSs increases the achievable rate significantly. Spectral efficiency is investigated in [21] when a user associates employing DU-CPL and DU-DPL access operating in μWave and mmWave band and effect of full-duplex interference on the spectral efficiency in two-tier HetNets. DU-DPL access with half and full-duplex communication is studied in [22] and it is shown that user-BS link throughput based on traffic pattern is enhanced significantly in HetNets. A study in [23] explores DU-DPL access where a user decides for cell association based on context information and results show that performance in the UL improves significantly with denser deployments of SLBs in HetNets. The approach in [24] nulls the interference nearby without taking help of message transmission, cooperation and enhances the DL performance of users employing DU-DPL access in HetNets. Outer approximation and heuristic algorithms are employed in [25] to investigate user association and power allocation to maximize sum-rate and balanced traffic offloading in the DL and UL using DU-CPL and DU-DPL access in HetNets. Results of this study show that DU-DPL access achieves higher user association, balanced traffic load in the UL, and enhanced sum-rate than its counterpart DU-CPL access. Sum-rate maximization objective along with minimum data rate and user transmit power constraints with user employing DU-DPL access in D2D-underlay HetNets has been investigated in [26]. This study shows that DU-DPL access surpasses its traditional counterpart DU-CPL access in terms of user association and sum-rate in HetNets. More recent work in [27] optimize communication energy efficiency using Q-learning and deep Q-learning power allocation schemes using DU-CPL and DU-DPL access schemes in UAV assisted HetNets. Results of this study show that the proposed power allocation scheme achieves better EE performance results than the conventional fractional power control scheme.

B. MOTIVATION AND CONTRIBUTION

After looking at Table. 1 and going through the past literature on the subject [11], [12], [14]–[16], [19]–[27] to the best of authors knowledge, challenges faced by beyond 5G HetNets, i.e., accommodating exponential increase in mobile users and scarce spectrum in μWave band etc has not been investigated in the past. In this work, we consider both challenges in HetNets comprising LHB and relay operating in μWave band and SLB and D2D operating in mmWave band. We formulate user association optimization problems to pitch a user association scheme based on DU-DPL access against traditional DU-CPL access in HetNets to gauge the performance of these access schemes in terms of accommodating users and spectrum efficiency. Formulated problems are non-deterministic polynomial-time hard (NP-hard) and solved using ϵ-optimal algorithm. The main contributions of this work are summarized below:

- This work investigates user association and allocation of power along with spectrum in μWave & mmWave bands in HetNets. We formulate UAM, TM, and RBM optimization problems based on DU-DPL access and DU-CPL access in HetNets to gauge the performance of these access schemes in HetNets. The formulated problems are mixed-integer non-linear programming (MINLP) problems where objective function and constraints are non-linear in HetNets.
- We use a two-stage ϵ-optimal algorithm based on branch and cut technique to solve MINLP problems. After fixing binary variables, MINLP problems are changed to the non-linear programming (NLP) problem and solved in stage-1. NLP problem solution is an upper bound of the optimal solution. In stage-2, results of stage-1 are used to change MINLP problems to mixed-integer linear programming (MILP) problems. MILP problem solution gives a lower bound of the optimal solution.
- Simulations and results verify the performance edge of DU-DPL access over DU-CPL access in terms of accommodating users, throughput, and spectrum efficiency in the latter part of the paper.

The rest of the paper is organized as follows: the network model, user access cases for cell association, and problem formulation for DU-CPL and DU-DPL access are discussed in Section II, the proposed algorithm, its convergence and complexity are discussed in section III, the simulations and numerical results are discussed in section IV. The conclusion is given in Section V.

II. NETWORK MODEL

This section presents a network model that leads to the formulation of the problem considering user association & throughput maximization, power allocation, and spectrum resources minimization using DU-CPL and DU-DPL access in N-tier HetNets.

A. SPATIAL MODEL

Fig. 1(a) and 1(b) show HetNets with DU-CPL and DU-DPL access. These HetNets are combination of LHB and relays operating in μWave band for seamless coverage supported by SLB and D2D operating in mmWave band. Let set of users is denoted by $\mathbb{I} \in \{1, 2, 3, 4...I\}$, set of μWave BSs is denoted by $\mathbb{J} \in \{l, r\}$ and set of mmWave BSs is denoted by $\mathbb{K} \in \{s, d\}$ where l = LHB, r = relay, s = SLB and d = D2D. We assume that user handset is equipped with μWave and mmWave interfaces for transmission in both frequency band [33].

Definition-1. Let 0/1 variable $x_{i,j}^{(\cdot)}$ denotes user i association with BS j, i.e., 1 when associated and 0 otherwise. Here, $(\cdot)$ = d represents DL and $(\cdot)$ = u represents UL.

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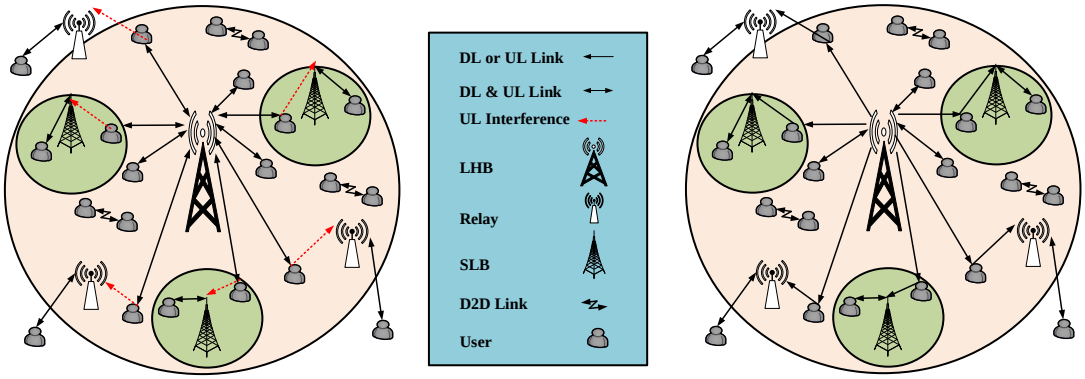

(a) DU-CPL access **(b) DU-DPL access**

FIGURE 1. **User association access strategies in HetNets.**

Definition-2. Let 0/1 variable $y_{i,k}^{(\cdot)}$ is a binary variable for user i association with BS k, i.e., 1 when associated and 0 otherwise.

Definition-3. Let $\alpha_j^{(\cdot)}$ & $\beta_k^{(\cdot)}$ denotes users associated with BS j and k, respectively where $\alpha_j^{(\cdot)} = \sum_{j\in\mathbb{J}} x_{i,j}^{(\cdot)}$ and $\beta_k^{(\cdot)} = \sum_{k\in\mathbb{K}} y_{i,k}^{(\cdot)}\ \forall\ i \in \mathbb{I}$

B. PROPAGATION MODEL

Using Friis transmission equation [11], [34], the channel gain between user i and BS j or k using μWave and mmWave channels are modelled below:

$$h_{i,j}^{(\cdot)} = \frac{h_{i,j}^{\mathrm{Tx}} h_{i,j}^{\mathrm{Rx}}}{\rho_{i,j}^{(\cdot)}}, \tag{1a}$$

$$h_{i,k}^{(\cdot)} = \frac{h_{i,k}^{\mathrm{Tx}} h_{i,k}^{\mathrm{Rx}}}{\rho_{i,k}^{(\cdot)}}, \tag{1b}$$

$$\rho_{i,j}^{(\cdot)} = 20log(\frac{4\pi}{\lambda_j}) + 10\delta_j log(d_{i,j}) + \theta_j, \tag{1c}$$

$$\rho_{i,k}^{(\cdot)} = \begin{cases} \Psi + 10(\delta_k^{\mathrm{L}})log(d_{i,k}) + \theta_k^{\mathrm{L}}, & \text{LOS link,} \\ \Psi + 10(\delta_k^{\mathrm{N}})log(d_{i,k}) + \theta_k^{\mathrm{N}}, & \text{otherwise.} \end{cases} \tag{1d}$$

where the wavelength and path loss in μWave band is denoted by λ_j and δ_j, respectively. The path loss exponents for LOS and NLOS links are denoted by δ_k^{L} & δ_k^{N}, the distances between user i & BS j or k are denoted by $d_{i,j}$ & $d_{i,k}$, the far field reference distance is denoted by d_o and the shadowing (in dB) for LOS and NLOS mmWave links are denoted by θ_k^{L} & θ_k^{N} which are a Gaussian random variable with zero mean and ς^2 variance [35]. In (1d), $\Psi = 32.4 + 20log(f_k)$ is the path loss in mmWave link with f_k as carrier frequency.

C. USER ACCESS CASES FOR CELL ASSOCIATION

1) DU-CPL access

This access technique ensures user i association with the same BS j or k in DL & UL basing on SRP criteria in the DL only [6]. This association case leads to interference in the UL by LHB cell edge users as shown in Fig. 1(a). This association case is mathematically modeled below:

$$j^* = argmax_{j\in\{l,r\}} \left(x_{i,j}^{\mathrm{d}} p_{i,j}^{\mathrm{d}} h_{i,j}^{\mathrm{d}}\right), \tag{2a}$$

$$k^* = argmax_{k\in\{s,d\}} \left(y_{i,k}^{\mathrm{d}} p_{i,k}^{\mathrm{d}} h_{i,k}^{\mathrm{d}}\right), \tag{2b}$$

$$x_{i,j^*}^{\mathrm{d}} = 1, \tag{2c}$$

$$y_{i,k^*}^{\mathrm{d}} = 1. \tag{2d}$$

where $p_{i,j}^{\mathrm{d}}$ and $p_{i,k}^{\mathrm{d}}$ is received power from BS j or k to user i in DL. $h_{i,j}^{\mathrm{d}}$ and $h_{i,k}^{\mathrm{d}}$ are channel gains from BS j or k to user i in DL.

2) DU-DPL access

This access technique ensure user i association with same or different BS j or k in DL & UL basing on SRP criteria in the DL [6] and WPL criteria in the UL [8]. This association case offloads LHB cell edge user to nearby other BS and thus avoids interference in the UL as shown in Fig. 1(b). This association case is mathematically modeled below:

$$j^* = argmax_{j\in\{l,r\}} \left(x_{i,j}^{\mathrm{d}} p_{i,j}^{\mathrm{d}} h_{i,j}^{\mathrm{d}}\right),\ argmin_{j\in\{l,r\}} \left(x_{i,j}^{\mathrm{u}} \rho_{i,j}^{\mathrm{u}}\right), \tag{3a}$$

$$k^* = argmax_{k\in\{s,d\}} \left(y_{i,k}^{\mathrm{d}} p_{i,k}^{\mathrm{d}} h_{i,k}^{\mathrm{d}}\right),\ argmin_{k\in\{s,d\}} \left(y_{i,k}^{\mathrm{u}} \rho_{i,k}^{\mathrm{u}}\right), \tag{3b}$$

$$x_{i,j^*}^{\mathrm{d}} = 1, x_{i,j^*}^{\mathrm{u}} = 1, \tag{3c}$$

$$y_{i,k^*}^{\mathrm{d}} = 1, y_{i,k^*}^{\mathrm{u}} = 1. \tag{3d}$$

where $\rho_{i,j}^{\mathrm{d}}$ and $\rho_{i,k}^{\mathrm{d}}$ is the path loss from user i to BS j or k in the UL.

D. SINR MODELS IN HETNETS

As per Slyvnyak's theorem [36], interference by nearby BS $j^{'}, k^{'}$ in the DL and MU $i^{'}$ in the UL operating in μWave or mmWave band is treated as noise. Mathematically, SINR at user i in the DL & BS j or k in the UL operating in μWave or mmWave band are given below:

$$\mathrm{SINR}^{\mathrm{d}}_{i,j} = \frac{p^{\mathrm{d}}_{i,j} h^{\mathrm{d}}_{i,j}}{\sum_{j' \in \mathbb{J}, j' \neq j} p^{\mathrm{d}}_{i',j'} h^{\mathrm{d}}_{i,j'} + \sigma^2}, \quad j \in \{l, r\} \,\&\, i \in \mathbb{I}, \tag{4a}$$

$$\mathrm{SINR}^{\mathrm{u}}_{i,j} = \frac{p^{\mathrm{u}}_{i,j} h^{\mathrm{u}}_{i,j}}{\sum_{i' \in \mathbb{I}, i' \neq i} p^{\mathrm{u}}_{i',j'} h^{\mathrm{u}}_{i',i} + \sigma^2}, \quad j \in \{l, r\} \;\&\; i \in \mathbb{I}, \tag{4b}$$

$$\mathrm{SNR}^{\mathrm{d}}_{i,k} = \frac{p^{\mathrm{d}}_{i,k} h^{\mathrm{d}}_{i,k}}{\sigma^2}, \; k \in \{s, d\} \,\&\, i \in \mathbb{I}, \tag{4c}$$

$$\mathrm{SNR}^{\mathrm{u}}_{i,k} = \frac{p^{\mathrm{u}}_{i,k} h^{\mathrm{u}}_{i,k}}{\sigma^2}, \; k \in \{s, d\} \,\&\, i \in \mathbb{I}. \tag{4d}$$

where σ^2 is the variance of the Additive White Gaussian Noise (AWGN).

E. CAPACITY CALCULATION

Achievable capacity using μWave and mmWave band are denoted by $c^{(\cdot)}_{i,j}$ and $c^{(\cdot)}_{i,k}$, respectively. Mathematically, achievable capacity using μWave and mmWave band is calculated below using Shannon's capacity formula:

$$c^{(\cdot)}_{i,j} = \frac{B^{(\cdot)}_j}{\sum_{j \in \mathbb{J}} x^{(\cdot)}_{i,j}} log_2 \left(1 + \mathrm{SINR}^{(\cdot)}_{i,j}\right), \tag{5a}$$

$$c^{(\cdot)}_{i,k} = \frac{B^{(\cdot)}_k}{\sum_{k \in \mathbb{K}} x^{(\cdot)}_{i,k}} log_2 \left(1 + \mathrm{SINR}^{(\cdot)}_{i,k}\right). \tag{5b}$$

where $\mathrm{SINR}^{(\cdot)}_{i,j}$ is modelled in (4a) and (4b) and $\mathrm{SINR}^{(\cdot)}_{i,k}$ is modelled in (4c) and (4d). μWave bandwidth $B^{(\cdot)}_j$ and mmWave bandwidth $B^{(\cdot)}_k$ is equally divided among associated users [37]

Resource blocks (RB) are allocated to user i by BS j or k depending upon the user's QoS rate requirements. Mathematically, the lower ceiling of RBs required by a user i to fulfill a particular QoS rate requirement is given below:

$$\eta^{(\cdot)}_{i,j} = \left\lceil \frac{Q^{(\cdot)}_{i,j}}{c^{(\cdot)}_{i,k}} \right\rceil, \tag{6a}$$

$$\eta^{(\cdot)}_{i,k} = \left\lceil \frac{Q^{(\cdot)}_{i,k}}{c^{(\cdot)}_{i,k}} \right\rceil. \tag{6b}$$

where $\eta^{(\cdot)}_{i,j}$ & $\eta^{(\cdot)}_{i,k}$ denotes minimum RBs requirement by a user i associated with BS j or k. $\lceil \cdot \rceil$ denotes ceiling function.

F. PROBLEM FORMULATION

We introduce the objective function, constraints and then formulate problems for DU-CPL and DU-DPL access in HetNets. The objective is defined below:

1) The objective of this paper is to maximize user association, throughput while utilizing minimum spectrum resources in μWave and mmWave bands. This objective is studied in [12], [13] where UAM, TM, and RBM optimization problems based on DU-DPL access and DU-CPL access are not considered. Based on (4), (5) and (6), the objective function considering UAM, TM and RBM is defined below:

$$\begin{aligned}\triangle(x, y, \eta) = &\left(\frac{|\alpha^{\mathrm{d}}_j|}{|I|}\right) \sum_{j \in \mathbb{J}} \sum_{i \in \mathbb{I}} \left(x^{\mathrm{d}}_{i,j} c^{\mathrm{d}}_{i,j}\right) - \left(1 - \frac{|\alpha^{\mathrm{d}}_j|}{|I|}\right) \sum_{j \in \mathbb{J}} \sum_{i \in \mathbb{I}} \left(x^{\mathrm{d}}_{i,j} \eta^{\mathrm{d}}_{i,j}\right) + \\ &\left(\frac{|\alpha^{\mathrm{u}}_j|}{|I|}\right) \sum_{j \in \mathbb{J}} \sum_{i \in \mathbb{I}} \left(x^{\mathrm{u}}_{i,j} c^{\mathrm{u}}_{i,j}\right) - \left(1 - \frac{|\alpha^{\mathrm{u}}_j|}{|I|}\right) \sum_{j \in \mathbb{J}} \sum_{i \in \mathbb{I}} \left(x^{\mathrm{u}}_{i,j} \eta^{\mathrm{u}}_{i,j}\right) + \\ &\left(\frac{|\beta^{\mathrm{d}}_k|}{|I|}\right) \sum_{k \in \mathbb{K}} \sum_{i \in \mathbb{I}} \left(y^{\mathrm{d}}_{i,k} c^{\mathrm{d}}_{i,k}\right) - \left(1 - \frac{|\beta^{\mathrm{d}}_k|}{|I|}\right) \sum_{k \in \mathbb{K}} \sum_{i \in \mathbb{I}} \left(y^{\mathrm{d}}_{i,k} \eta^{\mathrm{d}}_{i,k}\right) + \\ &\left(\frac{|\beta^{\mathrm{u}}_k|}{|I|}\right) \sum_{k \in \mathbb{K}} \sum_{i \in \mathbb{I}} \left(y^{\mathrm{u}}_{i,k} c^{\mathrm{u}}_{i,k}\right) - \left(1 - \frac{|\beta^{\mathrm{u}}_k|}{|I|}\right) \sum_{k \in \mathbb{K}} \sum_{i \in \mathbb{I}} \left(y^{\mathrm{u}}_{i,k} \eta^{\mathrm{u}}_{i,k}\right)\end{aligned} \tag{7a}$$

where $0 < \left(\frac{|\alpha^{(\cdot)}_j|}{|I|}\right) < 1$ and $0 < \left(\frac{|\beta^{(\cdot)}_k|}{|I|}\right) < 1$.

2) Using definition 1 and 2, the constraint to ensure that at most user associates with one BS in the DL and UL is given below:

$$\sum_{j \in \mathbb{J}} x^{\mathrm{d}}_{i,j} + \sum_{k \in \mathbb{K}} y^{\mathrm{d}}_{i,k} \leq 1, \; \forall\, i \in \mathbb{I}, \tag{8a}$$

$$\sum_{j \in \mathbb{J}} x^{\mathrm{u}}_{i,j} + \sum_{k \in \mathbb{K}} y^{\mathrm{u}}_{i,k} \leq 1, \; \forall\, i \in \mathbb{I}. \tag{8b}$$

3) The constraint to ensure that power is optimally allocated in the DL and UL is given below:

$$\sum_{j \in \mathbb{J}} p^{\mathrm{d}}_{i,j} - x^{\mathrm{d}}_{i,j} P^{\mathrm{d}}_j \leq 0, \; \sum_{k \in \mathbb{K}} p^{\mathrm{d}}_{i,k} - y^{\mathrm{d}}_{i,k} P^{\mathrm{d}}_k \leq 0 \; \forall\, i \in \mathbb{I}, \tag{9a}$$

$$p^{\mathrm{u}}_{i,j} - x^{\mathrm{u}}_{i,j} P^{\mathrm{u}}_i \leq 0, \; p^{\mathrm{u}}_{i,k} - y^{\mathrm{u}}_{i,k} P^{\mathrm{u}}_i \leq 0 \; \forall\, j \in \mathbb{J}, k \in \mathbb{K}, i \in \mathbb{I}. \tag{9b}$$

where P^{d}_j and P^{d}_k is maximum transmit power of μWave and mmWave BSs.

4) Using (1a), (1b) and (2), constraint to ensure user association basing on SRP criteria in the DL only, for DU-CPL access, is given below:

$$x^{\mathrm{d}}_{i,j} p^{\mathrm{d}}_{i,j} h^{\mathrm{d}}_{i,j} - p^{\mathrm{d}}_{i,j'} h^{\mathrm{d}}_{i,j'} \geq 0 \; \forall\, j \,\&\, j' \in \mathbb{J}, \; i \in \mathbb{I}, \tag{10a}$$

$$y^{\mathrm{d}}_{i,k} p^{\mathrm{d}}_{i,k} h^{\mathrm{d}}_{i,k} - p^{\mathrm{d}}_{i,k'} h^{\mathrm{d}}_{i,k'} \geq 0 \; \forall\, k \,\&\, k' \in \mathbb{K}, \; i \in \mathbb{I}. \tag{10b}$$

5) Using (1a), (1b), (1c), (1d) and (3), constraint to ensure user association basing on SRP criteria in the DL and WPL criteria in the UL, for DU-DPL access, is given below:

$$x^{\mathrm{d}}_{i,j} p^{\mathrm{d}}_{i,j} h^{\mathrm{d}}_{i,j} - p^{\mathrm{d}}_{i,j'} h^{\mathrm{d}}_{i,j'} \geq 0 \; \forall\, j \,\&\, j' \in \mathbb{J}, \; i \in \mathbb{I}, \tag{11a}$$

$$x^{\mathrm{u}}_{i,j} \rho^{\mathrm{u}}_{i,j} - \rho^{\mathrm{u}}_{i,j'} \leq 0 \; \forall\, j \,\&\, j' \in \mathbb{J}, \; i \in \mathbb{I}, \tag{11b}$$

$$y^{\mathrm{d}}_{i,k} p^{\mathrm{d}}_{i,k} h^{\mathrm{d}}_{i,k} - p^{\mathrm{d}}_{i,k'} h^{\mathrm{d}}_{i,k'} \geq 0 \; \forall\, k \,\&\, k' \in \mathbb{K}, \; i \in \mathbb{I}, \tag{11c}$$

$$y^{\mathrm{u}}_{i,k} \rho^{\mathrm{u}}_{i,k} - \rho^{\mathrm{u}}_{i,k'} \leq 0 \; \forall\, k \,\&\, k' \in \mathbb{K}, \; i \in \mathbb{I}. \tag{11d}$$

6) Using (5) and (6), constraint to ensure minimum RBs requirement of a user is given below:

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$$\sum_{j\in\mathbb{J}} \eta^{\mathrm{d}}_{i,j} - x^{\mathrm{d}}_{i,j} N^{\mathrm{d}}_{j} \leq 0, \sum_{j\in\mathbb{J}} \eta^{\mathrm{u}}_{i,j} - x^{\mathrm{u}}_{i,j} N^{\mathrm{u}}_{j} \leq 0 \; \forall \, i \in \mathbb{I}, \tag{12a}$$

$$\sum_{k\in\mathbb{K}} \eta^{\mathrm{d}}_{i,k} - y^{\mathrm{d}}_{i,k} N^{\mathrm{d}}_{k} \leq 0, \sum_{k\in\mathbb{K}} \eta^{\mathrm{u}}_{i,k} - y^{\mathrm{u}}_{i,k} N^{\mathrm{u}}_{k} \leq 0 \; \forall \, i \in \mathbb{I}. \tag{12b}$$

7) Using definitions 1 and 2,, constraint to ensure that user association as per DU-CPL access is given below:

$$\sum_{j\in\mathbb{J}} x^{\mathrm{d}}_{i,j} = x^{\mathrm{u}}_{i,j} \; \forall \, i \in \mathbb{I}, \tag{13a}$$

$$\sum_{k\in\mathbb{K}} y^{\mathrm{d}}_{i,k} = y^{\mathrm{u}}_{i,k} \; \forall \, i \in \mathbb{I}. \tag{13b}$$

G. PROBLEM FORMULATION FOR DU-CPL ACCESS

Problem formulation for DU-CPL access considers UAM, TM, and RBM for optimal resources allocation in HetNets. The symbols and notations used in problem formulation are summarized in Table 2. Mathematically UAM, TM and RBM optimization problem for DU-CPL access is formulated below:

$$\max_{x,y,\eta} \triangle(x, y, \eta) \tag{14a}$$

$$\text{s.t.} \sum_{j\in\mathbb{J}} x^{\mathrm{d}}_{i,j} + \sum_{k\in\mathbb{K}} y^{\mathrm{d}}_{i,k} \leq 1, \sum_{j\in\mathbb{J}} x^{\mathrm{u}}_{i,j} + \sum_{k\in\mathbb{K}} y^{\mathrm{u}}_{i,k} \leq 1 \; \forall \, i \in \mathbb{I}, \tag{14b}$$

$$\sum_{j\in\mathbb{J}} p^{\mathrm{d}}_{i,j} - x^{\mathrm{d}}_{i,j} P^{\mathrm{d}}_{j} \leq 0, \sum_{k\in\mathbb{K}} p^{\mathrm{d}}_{i,k} - y^{\mathrm{d}}_{i,k} P^{\mathrm{d}}_{k} \leq 0 \; \forall \, i \in \mathbb{I}, \tag{14c}$$

$$p^{\mathrm{u}}_{i,j} - x^{\mathrm{u}}_{i,j} P^{\mathrm{u}}_{i} \leq 0, \; p^{\mathrm{u}}_{i,k} - y^{\mathrm{u}}_{i,k} P^{\mathrm{u}}_{i} \leq 0 \; \forall \, j \in \mathbb{J}, k \in \mathbb{K}, i \in \mathbb{I}, \tag{14d}$$

$$x^{\mathrm{d}}_{i,j} p^{\mathrm{d}}_{i,j} h^{\mathrm{d}}_{i,j} - p^{\mathrm{d}}_{i,j'} h^{\mathrm{d}}_{i,j'} \geq 0 \; \forall \, j \,\&\, j' \in \mathbb{J}, \; i \in \mathbb{I}, \tag{14e}$$

$$y^{\mathrm{d}}_{i,k} p^{\mathrm{d}}_{i,k} h^{\mathrm{d}}_{i,k} - p^{\mathrm{d}}_{i,k'} h^{\mathrm{d}}_{i,k'} \geq 0 \; \forall \, k \,\&\, k' \in \mathbb{K}, \; i \in \mathbb{I}, \tag{14f}$$

$$\sum_{j\in\mathbb{J}} \eta^{\mathrm{d}}_{i,j} - x^{\mathrm{d}}_{i,j} N^{\mathrm{d}}_{j} \leq 0, \sum_{j\in\mathbb{J}} \eta^{\mathrm{u}}_{i,j} - x^{\mathrm{u}}_{i,j} N^{\mathrm{u}}_{j} \leq 0 \; \forall \, i \in \mathbb{I}, \tag{14g}$$

$$\sum_{k\in\mathbb{K}} \eta^{\mathrm{d}}_{i,k} - y^{\mathrm{d}}_{i,k} N^{\mathrm{d}}_{k} \leq 0, \sum_{k\in\mathbb{K}} \eta^{\mathrm{u}}_{i,k} - y^{\mathrm{u}}_{i,k} N^{\mathrm{u}}_{k} \leq 0 \; \forall \, i \in \mathbb{I}, \tag{14h}$$

$$\sum_{j\in\mathbb{J}} x^{\mathrm{d}}_{i,j} = x^{\mathrm{u}}_{i,j} \; \forall \, i \in \mathbb{I}, \tag{14i}$$

$$\sum_{k\in\mathbb{K}} y^{\mathrm{d}}_{i,k} = y^{\mathrm{u}}_{i,k} \; \forall \, i \in \mathbb{I}, \tag{14j}$$

$$P^{\mathrm{d}}_{j} \geq p^{\mathrm{d}}_{i,j} \geq 0, \; P^{\mathrm{d}}_{k} \geq p^{\mathrm{d}}_{i,k} \geq 0 \; \forall \, , j \in \mathbb{J}, k \in \mathbb{K}, i \in \mathbb{I}. \tag{14k}$$

where tuning weights $\frac{|\alpha^{(\cdot)}_{j}|}{|I|}$ and $\frac{|\beta^{(\cdot)}_{k}|}{|I|} \in [0, 1]$. Constraint (14b) ensures user i association with one BS j or k in the DL & UL. Constraint (14c) ensures transmit power limits of BS j & k in the DL. Constraint (14d) ensures transmit power limit of user i in the UL. Constraints (14e) and (14f) ensures user association with BS j or k basing on SRP in the DL only. Constraints (14g) and (14h) ensures minimum QoS rate and minimum RBs. Constraints (14i) and (14j) ensures user association with same BS j or k in the DL & UL, respectively. Constraint (14k) ensures range of received power from BS j or k.

H. PROBLEM FORMULATION FOR DU-DPL ACCESS

Problem formulation for DU-DPL access considers UAM, TM and RBM for optimal resources allocation in HetNets. Mathematically UAM, TM and RBM optimization problem for DU-DPL access is formulated below:

$$\max_{x,y,\eta} \triangle(x, y, \eta) \tag{15a}$$

$$\text{s.t.} \sum_{j\in\mathbb{J}} x^{\mathrm{d}}_{i,j} + \sum_{k\in\mathbb{K}} y^{\mathrm{d}}_{i,k} \leq 1, \sum_{j\in\mathbb{J}} x^{\mathrm{u}}_{i,j} + \sum_{k\in\mathbb{K}} y^{\mathrm{u}}_{i,k} \leq 1 \; \forall \, i \in \mathbb{I}, \tag{15b}$$

$$\sum_{j\in\mathbb{J}} p^{\mathrm{d}}_{i,j} - x^{\mathrm{d}}_{i,j} P^{\mathrm{d}}_{j} \leq 0, \sum_{k\in\mathbb{K}} p^{\mathrm{d}}_{i,k} - y^{\mathrm{d}}_{i,k} P^{\mathrm{d}}_{k} \leq 0 \; \forall \, i \in \mathbb{I}, \tag{15c}$$

$$p^{\mathrm{u}}_{i,j} - x^{\mathrm{u}}_{i,j} P^{\mathrm{u}}_{i} \leq 0, \; p^{\mathrm{u}}_{i,k} - y^{\mathrm{u}}_{i,k} P^{\mathrm{u}}_{i} \leq 0 \; \forall \, j \in \mathbb{J}, k \in \mathbb{K}, i \in \mathbb{I}, \tag{15d}$$

$$x^{\mathrm{d}}_{i,j} p^{\mathrm{d}}_{i,j} h^{\mathrm{d}}_{i,j} - p^{\mathrm{d}}_{i,j'} h^{\mathrm{d}}_{i,j'} \geq 0 \; \forall \, j \,\&\, j' \in \mathbb{J}, \; i \in \mathbb{I}, \tag{15e}$$

$$x^{\mathrm{u}}_{i,j} \rho^{\mathrm{u}}_{i,j} - \rho^{\mathrm{u}}_{i,j'} \leq 0 \; \forall \, j \,\&\, j' \in \mathbb{J}, \; i \in \mathbb{I}, \tag{15f}$$

$$y^{\mathrm{d}}_{i,k} p^{\mathrm{d}}_{i,k} h^{\mathrm{d}}_{i,k} - p^{\mathrm{d}}_{i,k'} h^{\mathrm{d}}_{i,k'} \geq 0 \; \forall \, k \,\&\, k' \in \mathbb{K}, \; i \in \mathbb{I}, \tag{15g}$$

$$y^{\mathrm{u}}_{i,k} \rho^{\mathrm{u}}_{i,k} - \rho^{\mathrm{u}}_{i,k'} \leq 0 \; \forall \, k \,\&\, k' \in \mathbb{K}, \; i \in \mathbb{I}, \tag{15h}$$

$$\sum_{j\in\mathbb{J}} \eta^{\mathrm{d}}_{i,j} - x^{\mathrm{d}}_{i,j} N^{\mathrm{d}}_{j} \leq 0, \sum_{j\in\mathbb{J}} \eta^{\mathrm{u}}_{i,j} - x^{\mathrm{u}}_{i,j} N^{\mathrm{u}}_{j} \leq 0 \; \forall \, i \in \mathbb{I}, \tag{15i}$$

$$\sum_{k\in\mathbb{K}} \eta^{\mathrm{d}}_{i,k} - y^{\mathrm{d}}_{i,k} N^{\mathrm{d}}_{k} \leq 0, \sum_{k\in\mathbb{K}} \eta^{\mathrm{u}}_{i,k} - y^{\mathrm{u}}_{i,k} N^{\mathrm{u}}_{k} \leq 0 \; \forall \, i \in \mathbb{I}, \tag{15j}$$

$$P^{\mathrm{d}}_{j} \geq p^{\mathrm{d}}_{i,j} \geq 0, \; P^{\mathrm{d}}_{k} \geq p^{\mathrm{d}}_{i,k} \geq 0 \; \forall \, , j \in \mathbb{J}, k \in \mathbb{K}, i \in \mathbb{I}. \tag{15k}$$

where tuning weights $\frac{|\alpha^{(\cdot)}_{j}|}{|I|}$ and $\frac{|\beta^{(\cdot)}_{k}|}{|I|} \in [0, 1]$. Constraint (15b) ensures user i association with one BS j or k in the DL & UL. Constraint (15c) ensures transmit power limits of BS j & k in the DL. Constraint (15d) ensures transmit power limit of user i in the UL. Constraints (15e) and (15f) ensures user association with BS j basing on SRP and WPL in the DL & UL, respectively. Constraints (15g) and (15h) ensures user association with BS k basing on SRP and WPL in the DL & UL, respectively. Constraints (15i) and (15j) ensures minimum QoS rate and minimum RBs. Constraint (15k) ensures range of received power from BS j or k.

III. PROPOSED ALGORITHM

The problems in (14) & (15) are mix of binary and non-linear variables which is classical example of MINLP problem. Search space of the formulated problems increases exponentially as the number of users is increased in the simulations, i.e., $2^{|I|}$ optimization problems need a solution in each iteration. So, even in a small size network, the computational complexity of the formulated problems is not feasible in presence of binary variables. Hence, this kind of user association and power allocation problems are complex and NP-hard [38]. Therefore, we use ϵ-optimal algorithm to solve the formulated problems. ϵ-optimal algorithm uses the

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TABLE 2. List of notations

Notations	Definitions	Notations	Definitions
I	Total users	P_j^{d}	BS j maximum transmit power
$\alpha_j^{(\cdot)}$	Users associated with BS j	P_k^{d}	BS k maximum transmit power
$\beta_k^{(\cdot)}$	Users associated with BS k	P_i^{u}	User I maximum transmit power
J	Number of μWave BSs	$p_{i,j}^{\mathrm{d}}$	Transmit power by BS j to user i
K	Number of mmWave BSs	$p_{i,k}^{\mathrm{d}}$	Transmit power by BS k to user i
$\rho_{i,j}^{\mathrm{u}}$	Path loss from user i to BS j in UL using μWave channel	$p_{i,j}^{\mathrm{u}}$	Transmit power by user i to BS j
$\rho_{i,k}^{\mathrm{u}}$	Path loss from user i to BS k in UL using mmWave channel	$p_{i,k}^{\mathrm{u}}$	Transmit power by user i to BS k
$Q_{i,j}^{(\cdot)}$	Minimum QoS rate using μWave band	$h_{i,j}^{\mathrm{d}}$ & $h_{i,k}^{\mathrm{d}}$	Channel power gains in DL for μWave and mmWave channels
$Q_{i,k}^{(\cdot)}$	Minimum QoS rate using mmWave band	$h_{i,j}^{Tx}$ & $h_{i,j}^{Rx}$	Transmitter & receiver antenna gain in μWave band
$N_j^{(\cdot)}$	Number of μWave RBs	$h_{i,k}^{Tx}$ & $h_{i,k}^{Rx}$	Transmitter & receiver antenna gain in mmWave band
$N_k^{(\cdot)}$	Number of mmWave RBs	C_{b-k}	Constraint b to constraint k

principle of decomposition and divides the problem into the below sub-problems:

- Non-linear programming (NLP) problem.
- Mixed-integer linear programming (MILP) problem.

NLP and MILP problems are less complex, hence, ϵ-optimal algorithm converges within finite iterations, and gives ϵ optimal solution [39], [40].

A. DESCRIPTION OF ϵ-OPTIMAL ALGORITHM

Let Θ and $\psi_{\text{b-k}}$ denote objective function and constraints of problems in (14) or (15). $\mathbb{B}$ denotes binary variables $\mathbb{B} = \{x_{i,j}^{(\cdot)}, y_{i,k}^{(\cdot)}\}$, $\mathbb{P} = \{p_{i,j}^{(\cdot)}, p_{i,k}^{(\cdot)}\}$ and $\mathbb{S} = \mathbb{B} \cup \mathbb{P}$. Following four prepositions hold true for the Problems in (14) & (15):

1) $\mathbb{P}$ is compact, non-empty and convex.
2) The objective function Θ and $\psi_{\text{b-k}}$ are convex in $\mathbb{P}$ for fixed $\mathbb{S}$.
3) Θ and $\psi_{\text{b-k}}$ are differentiable with fixed $\mathbb{S}$.
4) Fixing $\mathbb{S}$ changes MINLP to NLP problem whose exact solution is possible.

1) Stage-1

In stage-1, $\mathbb{S}$ is fixed at $\mathbb{S}^n$ to transform the MINLP problems in (14) & (15) to NLP problem. The solution of NLP problem is upper bound of the optimal solution. The NLP problem is given below:

$$\min_{\mathbb{P}} \quad -\Theta(\mathbb{S}^n, \mathbb{P}) \tag{16a}$$

$$\text{s.t.} \quad \psi_{\text{b-k}}(\mathbb{S}^n, \mathbb{P}) \leq 0 \tag{16b}$$

2) Stage-2

Solving NLP problem in (16) gives binary variables of $\mathbb{S}$ at $\mathbb{S}^n$. In stage-2, results of stage-1 are used to transform the MINLP problems in Eq (14) & (15) to MILP problem. The MILP problem is given below:

$$\min_{\mathbb{S}} \min_{\mathbb{P}} \quad -\Theta(\mathbb{S}^n, \mathbb{P}) \tag{17a}$$

$$\text{s.t.} \quad \psi_{\text{b-k}}(\mathbb{S}^n, \mathbb{P}) \leq 0 \tag{17b}$$

(17) can be rewritten as:

$$\min_{\mathbb{S}} \quad -\tau(\mathbb{S}) \tag{18}$$

such that

$$\tau(\mathbb{S}) \quad = \min_{\mathbb{P}} \quad -\Theta(\mathbb{S}^n, \mathbb{P}) \tag{19a}$$

$$\text{s.t.} \quad \psi_{\text{b-k}}(\mathbb{S}^n, \mathbb{P}) \leq 0 \tag{19b}$$

The problem in (18) is the projection of (14) & (15) on $\mathbb{S}$ space. As all constraints hold for the NLP problem in (16) for all $\mathbb{S}^n$,so solution of projection problem can be written as under:

$$\min_{\psi} \min_{\mathbb{P}} \quad -\Theta(\mathbb{S}^n, \mathbb{P}^n) - \nabla\Theta(\mathbb{S}^n - \mathbb{P}^n)\begin{pmatrix}\mathbb{P} - \mathbb{P}^n \\ \mathbb{S} - \mathbb{S}^n\end{pmatrix} \tag{20a}$$

$$\text{s.t.} \quad \psi_{\text{b-k}}(\mathbb{S}^n, \mathbb{P}^n) - \nabla\psi_{\text{b-k}}(\mathbb{S}^n, \mathbb{P}^n)\begin{pmatrix}\mathbb{P} - \mathbb{P}^n \\ \mathbb{S} - \mathbb{S}^n\end{pmatrix} \leq 0. \tag{20b}$$

Lets a new variable ν is introduced then problem in (20) can be written as under:

$$\min_{\psi, \mathbb{P}, \nu} \quad \nu \tag{21a}$$

$$\text{s.t.} \quad \nu \geq -\Theta(\mathbb{S}^n, \mathbb{P}^n) - \nabla\Theta(\mathbb{S}^n - \mathbb{P}^n)\begin{pmatrix}\mathbb{P} - \mathbb{P}^n \\ \mathbb{S} - \mathbb{S}^n\end{pmatrix} \tag{21b}$$

$$\psi_{\text{b-k}}(\mathbb{S}^n, \mathbb{P}^n) - \nabla\psi_{\text{b-k}}(\mathbb{S}^n, \mathbb{P}^n)\begin{pmatrix}\mathbb{P} - \mathbb{P}^n \\ \mathbb{S} - \mathbb{S}^n\end{pmatrix} \leq 0 \tag{21c}$$

MILP problem in (21) gives lower bound of the optimal solution. The MILP problem is solved by branch and bound algorithm [41]. The solution of NLP problem at $\mathbb{S}^n$ drives the MILP problem when objective and constraints functions, i.e., Θ & $\psi_{\text{b-k}}$ etc are linear [42], [43]. The iterative approach of ϵ-optimal algorithm follows below steps:

1) The upper bound decreases and lower bound increases as the algorithm progress to achieve ϵ optimal solution.
2) Solution is optimal if the difference of lower and upper bound is below ϵ.
3) In case difference is more than ϵ, new binary variables $\mathbb{S}$ are fixed at $\mathbb{S}^{n+1}$. NLP and MILP problems are solved

again in the next iteration to get new upper and lower bounds.

4) The optimal solution is achieved when the upper and lower bound difference is less than ϵ.
5) ϵ-optimal algorithm flow chart is displayed in Fig. 2.

B. ALGORITHM CONVERGENCE AND OPTIMALITY

The ϵ-optimal algorithm converges in a linear manner as per [39], [42]. Objective function Θ and constraints $\psi_{\text{b-k}}$ are convex when binary variables $\mathbb{S}$ are fixed at $\mathbb{S}^n$. ϵ-optimal algorithm employs branch and cut method [41] to achieve an optimal solution, in finite steps, within $\epsilon = 10^{-3}$ when all four prepositions are satisfied. $\mathbb{P}$ is optimal as per (21) which describes that ν is greater than $\Theta(\mathbb{S}^n, \mathbb{P}^n)$ for any feasible point in (17). No feasible solution for the MILP problem exists for known binary variable $\mathbb{S}$, when ν is less than $\Theta(\mathbb{S}^n, \mathbb{P}^n)$. Therefore, MILP problem in (21) will not contain a value of $\mathbb{S}^n$ that is not having a feasible solution. This leads ϵ-optimal algorithm to converge in finite steps.

C. COMPLEXITY OF ϵ-OPTIMAL ALGORITHM

The complexity is calculated by flops [1] [44]. The initialization stage of ϵ-optimal algorithm adds to 5 flops. Solution of NLP problem adds $2IJK$ and $4IJK\psi$ flops. Solution of MILP problem adds $4IJK\psi$ and $2IJK\psi$ flops. Comparison of NLP and MILP problem adds 2 flops. Guessing new binary variables add 4 flops. The complexity of ϵ-optimal algorithm in terms of flops is given below:

$$F = 5 + 2IJK + 4IJK\psi + 4IJK\psi + 2IJK\psi + 4, \quad (22a)$$

$$F = 9 + 2IJK + 10IJK\psi, \quad (22b)$$

$$F \approx 2IJK + 10IJK\psi. \quad (22c)$$

Similarly, ϵ-optimal algorithm complexity representation by Big O is $O(I \times J \times K) + O(I \times J \times K \times \psi)$. Where I, J, K, and ψ denotes users, μWave BSs, mmWave BSs, and constraints, respectively.

IV. SIMULATION AND NUMERICAL RESULTS

This section includes simulation results based on optimal solution of the formulated problems in (14) & (15) employing ϵ-optimal algorithm. Performance in terms of optimal radio resource allocation is evaluated when using DU-CPL and DU-DPL access in N-tier HetNets. The LHB, with 1000 m radial coverage [7], is assumed to be located in the center, and relay, SLB, and D2D are randomly distributed/located within the coverage of LHB. 300 m,300 m and 50 m is coverage of SLB, relay and D2D, respectively [7], [45]. Simulations are run for a minimum of 5 users and a maximum of 40 users competing for allocation of radio resources such as BS, power, and RBs in HetNets. Table 3 shows parameters used in simulations.

[1] A flop is a floating-point operation and complexity is measured by the number of flops. In addition, division or multiplication operation adds to 1 flop. Complex addition adds 2 flops and complex multiplication adds 4 flops. $l \times m$ dimension matrix multiplication by $m \times o$ dimension matrix adds to $2lmo$ flops. The logical operator adds 1 flop and the assignment operator adds 1 flop. The $log_2(x)$ operator takes 2 flops

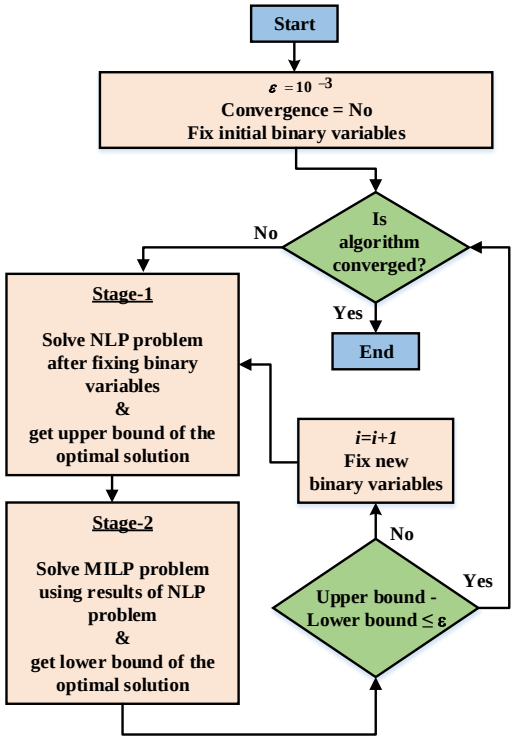

FIGURE 2. Flow chart - ϵ-optimal algorithm

TABLE 3. Simulation Parameters

Parameter	Value	Parameter	Value
f_j,	2 GHz	Q_i^{d}	{.2,.4,.6,.8,1} bps/Hz
f_k,	28 GHz	Q_j^{u}	{.2,.4,.6,.8,1} bps/Hz
θ_j	4 dB	$h_{i,j}^{Tx}$ & $h_{i,j}^{Rx}$	1 & 1
θ_k^{L}	8.66 dB	$h_{i,k}^{Tx}$ & $h_{i,k}^{Rx}$	1 & 1
θ_k^{N}	9.02 dB	δ_j	3
P_l^{d}	46 dBm	δ_k^{L}	2.55
P_s^{d}	25 dBm	δ_k^{N}	5.76
P_r^{d}	30 dBm	$N_j^{(\cdot)}$	50 RBs
P_d^{d}	23 dBm	$N_k^{(\cdot)}$	50 RBs
P_i^{u}	23 dBm	-	-

A. USERS ASSOCIATION

In this subsection, performance in terms of user association is evaluated when users are trying to associate in the HetNets and achieve minimum QoS data rate {0.2, 0.4, 0.6, 0.8, 1.0} Bps/Hz using spectrum resources in μWave and mmWave band employing DU-CPL and DU-DPL strategies in N-tier HetNets.

Performance in terms of user association, in the DL and UL, for different QoS data rates in μWave and mmWave bands using DU-CPL access versus DU-DPL access in N-tier HetNets is shown in Fig. 3 and 4. On average users

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association with SLS and D2D in mmWave band is better as compared to LHS and relay operating in μWave band for both DU-CPL and DU-DPL strategies. This users association pattern dictates that majority of users, with good LOS, preferred BSs operating in mmWave band where higher data rate requirements are met effectively and the minority of the users, NLOS users, associate with LHS and relay operating in μWave band with blanket coverage in HetNets. When it comes to user association performance versus QoS data rate using DU-CPL access, users association is maximum when QoS data rate is minimum and starts dropping significantly as QoS data rate is increased from 0.2 Bps/Hz to 1.0 Bps/Hz with a step size of 0.2 Bps/Hz. The key factors for this degrading performance are inefficient utilization of limited available power, RBS and the binding on a user to associate with a BS in the DL and UL as per SRP in the DL only. However, the effect of an increase in QoS data rate on user association, in the DL and UL, performance is marginal when employing DU-DPL access. The key factor for this consistent performance are efficient utilization of limited available power, RBS and the free choice to the users for association in the DL and UL based on SRP and WPL, respectively. Thus, DU-DPL access performs much better than DU-CPL access when it comes to user association versus different QoS data rates in HetNets.

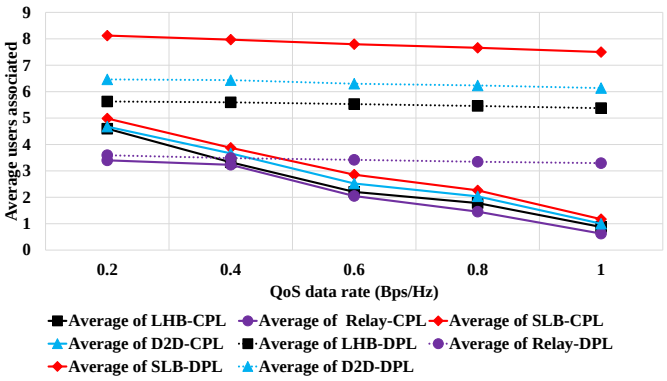

FIGURE 3. Users association using DU-CPL versus DU-DPL access in the DL.

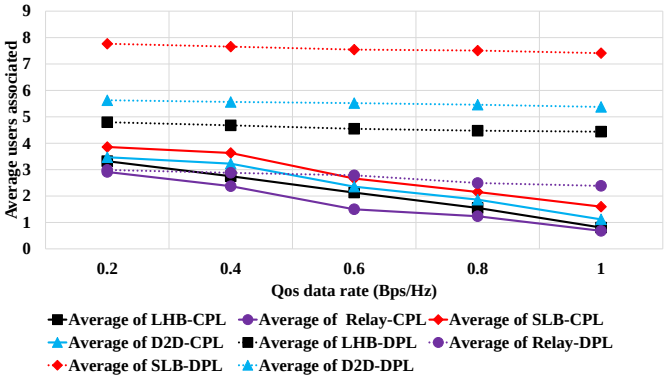

FIGURE 4. Users association using DU-CPL versus DU-DPL access in the UL.

B. USERS ASSOCIATION - DATA RATE

Performance in terms of user association and achieved data rate for different QoS data rates in μWave and mmWave bands using DU-CPL access in HetNets in the DL and UL is shown in Fig. 5 and 6, respectively. On the average in the DL and UL, Fig. 5 and 6 show that users association and achieved data rate is maximum when QoS data rate is 0.2 Bps/Hz. However, users association and achieved data rates drop significantly when the QoS data rate is increased from 0.2 Bps/Hz to 1.0 Bps/Hz with a step size of 0.2 Bps/Hz. This degrading performance, for users association and achieved data rate, depicts that DU-CPL access accommodates minimum users at higher QoS data rates and affects achieved data rate significantly in HetNets. The obvious reasons for such degrading performance at higher QoS data rates inefficient utilization of available power, RBs and binding on the user to decide association with the same BS based on SRP in the DL only.

Performance in terms of user association and achieved data rate for different QoS data rates in μWave and mmWave bands using DU-DPL access in HetNets in the DL and UL is shown in Fig. 7 and 8, respectively. Dividends of freedom given to users to decouple DL and UL on user association viz-a-viz achieved data rate are shown in Fig. 7 and 8. On average in the DL and UL, users association and achieved data rate, in the DL and UL, is maximum when QoS data rate is minimum, e.g.,0.2 Bps/Hz. However, a marginal decrease in users association and achieve data rate is observed when the QoS data rate is increased from 0.2 Bps/Hz to 1.0 Bps/Hz. Thus user association based on SRP in the DL and WPL in the UL helps users to remain attached with different BSs even at higher QoS data rates in the HetNets. Moreover, DU-DPL access utilizes available limited power and RBs efficiently. Overall, network performance in terms of user association and achieved rate using DU-DPL access is much better than using DU-CPL access in HetNets.

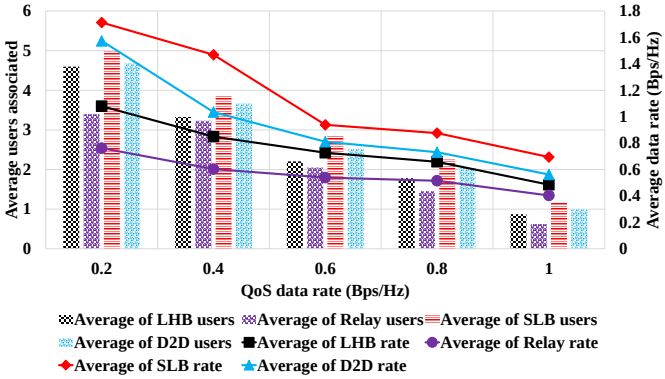

FIGURE 5. Users association-data rate versus QoS requirements using DU-CPL access in the DL.

C. RBS - DATA RATE

Performance of DU-CPL access in terms of used RBs in μWave and mmWave bands and achieved data rate versus the number of users (I) in the DL and UL is shown in Fig.

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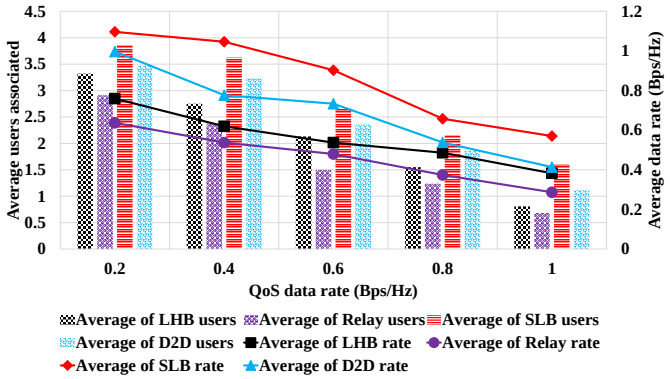

FIGURE 6. Users association-data rate versus QoS requirements using DU-CPL access in the UL.

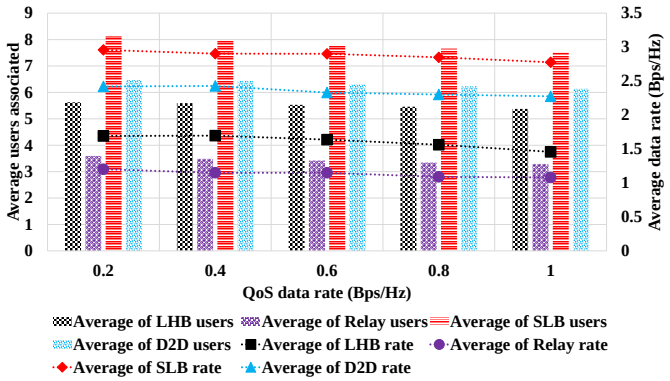

FIGURE 7. Users association-data rate versus QoS requirements using DU-DPL access in the DL.

9 and 10, respectively. Here, a minimum of 5 users and a maximum of 40 users with a step size of 5 users in each iteration try to achieve minimum QoS data rate {0.2, 0.4, 0.6, 0.8, 1.0} Bps/Hz employing DU-CPL access in HetNets. Maximum spectrum resources in μWave and mmWave bands are available for a single user when competing users in the network are minimum, e.g., 5 users and vice versa. Moreover, user association drops when QoS data rate is increased using DU-CPL access as seen earlier in Fig. 3 and 4. Hence, the average achieved data rate is maximum for minimum competing users. As the number of users (I) are increased in the simulations, the number of RBs per user decreases, and

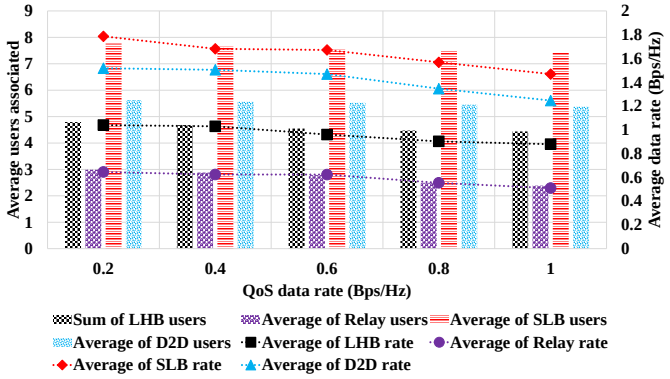

FIGURE 8. Users association-data rate versus QoS requirements using DU-DPL access in the UL.

hence average achieved data rate also decreases. Thus, on the average in the DL and UL, the achieved data rate is maximum for minimum users and minimum for maximum users as shown in Fig. 9 and 10. Moreover, simulation results show that spectrum resources utilization tendency is maximum in mmWave band and minimum in μWave band. This validates our finding in Fig. 3 and 4 that maximum users associate with SLB and D2D operating in mmWave band and minimum users associate with LHB and relay operating in μWave band. Moreover, results in section IV-A and IV-B shows that user association drops significantly at higher QoS data rates. Thus, on the average in the DL and UL, percentage RBs utilization also drops as shown in Fig. 9 and 10 viz-a-viz significant drop in data rate when using DU-CPL access in HetNets. Thus user association based on SRP in the DL only does not help in efficient spectrum resources utilization viz-a-viz achieved data rate in HetNets.

Performance of DU-DPL access in terms of used RBs in μWave and mmWave bands and achieved data rate versus the number of users (I)in the DL and UL is shown in Fig. 11 and 12, respectively. Here, a minimum of 5 users and a maximum of 40 users with a step size of 5 users in each iteration try to achieve minimum QoS data rate {0.2, 0.4, 0.6, 0.8, 1.0} Bps/Hz employing DU-DPL access in HetNets. In this setup, maximum spectrum resources in μWave and mmWave band are available for a single user when competing users are minimum, e.g., 5 users in HetNets and vice versa. Hence, on the average in the DL and UL, the achieved data rate is maximum when competing users are minimum, e.g., 5 users in HetNets and vice versa as shown in Fig. 11 and 12. Simulation results plotted in Fig. 11 and 12 also shows that spectrum resources utilization tendency is maximum in untapped mmWave band and minimum in scarce μWave band.

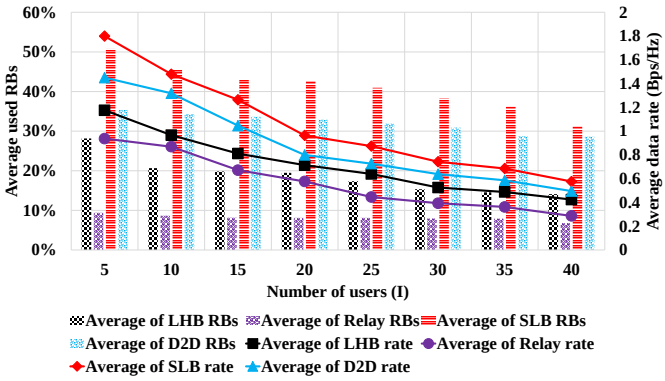

FIGURE 9. RBs-data rate versus QoS requirements using DU-CPL access in the DL.

This validates our finding in Fig. 3 and 4 that maximum users associate with SLB and D2D operating in mmWave band and minimum users associate with LHB and D2D operating in μWave band. Moreover, results in section IV-A and IV-B shows that user association drops marginally at higher QoS data rates. Thus, on the average in the DL and UL, percentage RBs utilization also drops marginally as shown in Fig. 9 and 10 viz-a-viz marginal drop in data rate when using

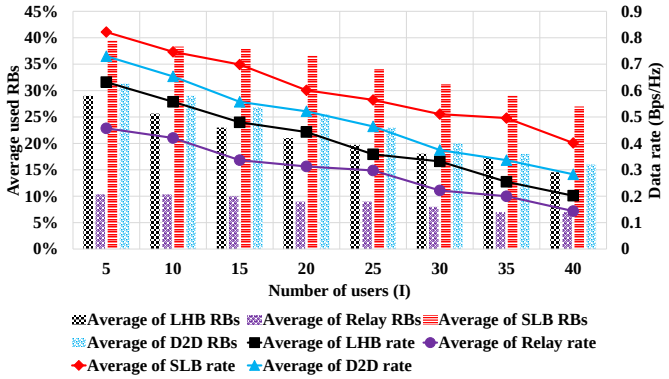

FIGURE 10. RBs-data rate versus QoS requirements using DU-CPL access in the UL.

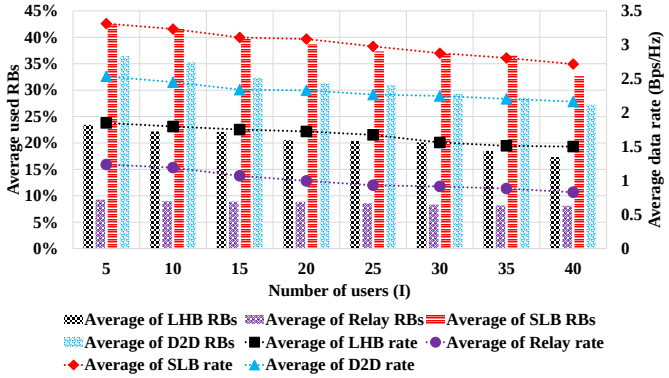

FIGURE 11. RBs-data rate versus QoS requirements using DU-DPL access in the DL.

DU-DPL access in HetNets. Thus user association based on SRP in the DL and WPL in the UL helps maximum users to associate and consume spectrum resources in un-taped mmWave band as compared to μWave band efficiently and achieve higher data rates in HetNets.

V. CONCLUSION

This work investigates user association, throughput, and spectrum efficiency while operating in μWave and mmWave bands in HetNets. Novel DU-DPL access is pitched against traditional DU-CPL access to gauge performance in terms of accommodating users, throughput, and spectrum efficiency. A two-stage ϵ-optimal algorithm is used to solve the problems formulated for DU-CPL and DU-DPL access to get the optimal solution. Simulations results demonstrate that DU-DPL access achieves maximum user association, higher data rate, and efficient spectrum resources utilization in μWave and mmWave bands than its counterpart DU-CPL access. Moreover, simulation results gave an insight of the HetNets that the majority of the users prefer association with BSs operating in un-tapped mmWave band than scarce μWave band to fulfill higher data rate requirements in the beyond 5G HetNets.

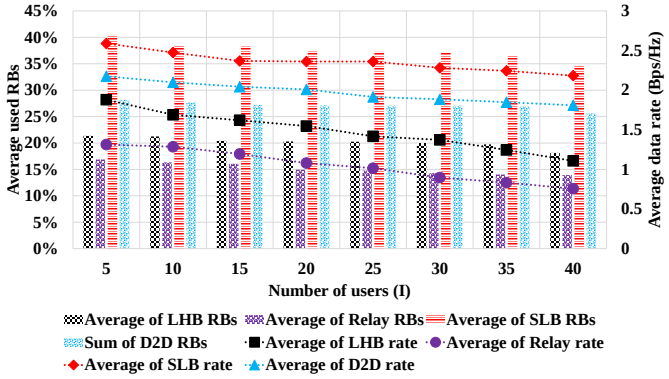

FIGURE 12. RBs-data rate versus QoS requirements using DU-DPL access in the UL.

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