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Energy-Efficient Approach for Beamforming Design and BBUs Aggregation in Heterogeneous C-RAN

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Abstract—Heterogeneous cloud radio access network (C-RAN) that combines the benefits of C-RAN and multi-tier heterogeneous networks (HetNets) is emerged as a novel network solution for improving both spectrum and energy efficiencies. In this work, we propose an energy-efficient approach that considers both RRHs beamforming design and BBUs aggregation in heterogeneous C-RAN. First, the problem is formulated as an optimization problem to maximize the weighted energy efficiency utility function subject to BBU processing capability, per-user quality-of-service (QoS) requirement and per-RRH total transmit power constraints. Then, the optimization problem is decomposed into two sub problems. The first sub problem is a transmit beamforming vectors optimization problem. This problem is transformed to a weighted sum mean square error (MSE) minimization problem and solved using a weighted minimum mean square error (WMMSE) algorithm. The second sub problem is the BBUs aggregation problem. This problem is converted to a bin packing problem and we propose an algorithm based on the Best-Fit-Decreasing method to solve it. In order to show the effectiveness of the proposed energy-efficient approach, we compare it with different algorithms that are presented in the literature.

Index Terms—Heterogeneous cloud radio access network, beamforming, weighted minimum mean square error (WMMSE), Best-Fit-Decreasing.

I. INTRODUCTION

Heterogeneous cloud radio access network (C-RAN) that combines the benefits of C-RAN and

multi-tier heterogeneous networks (HetNets) is emerged as a novel network solution for improving both spectrum and energy efficiencies [1]. Small cells-based HetNets have proven their potential to satisfy the dramatic growth of capacity demand by allowing more efficient spatial spectrum reuse and traffic offload. This can be achieved by embedding several low power nodes with full frequency reuse underlying macro cell base stations (BSs) [2]. In parallel with the development of HetNets, C-RAN has been considered as an innovative access network that can improve the traditional cellular network performance. In C-RAN, the BS is decoupled into two parts: remote radio head (RRH) and baseband unit (BBU). BBUs are collected into a centralized location called BBU pool and connected through fronthaul links to RRHs [3]. Therefore, coordinated multi-point (CoMP) transmission techniques can be employed in C-RAN to increase the spectrum efficiency.

In literature, many research works have been conducted for the optimization of transmit beamforming vectors and/or BBUs aggregation under different system constraints. In these works many objective functions are considered such as rate maximization and power minimization. In [4], the authors jointly optimize the virtual machine (VM) activation and sparse beamforming in order to minimize the overall cost for a C-RAN with limited fronthaul capacity and system delay constraints. The beamforming vector design and BBU processing resource allocation problem is studied in [5] to minimize the energy cost while satisfying the fronthaul limitations and the time constraints. In [6], the authors propose a dynamic BBU-RRH mapping scheme to allocate the resources dynamically to RRHs in an efficient way using a borrow-and-lend approach. The RRH mode, user association

and beamforming vectors optimization problem is studied in [7] to minimize the overall power consumption under the quality-of-service (QoS) requirements for each user and the RRHs transmit power constraints. The authors in [8] consider the user association and the BBU-RRH mapping optimization problem to minimize the system cost under per-user QoS constraints. The beamforming optimization problem is considered in [9] to maximize the sum-rate under per-RRH power and fronthaul capacity constraints. The BBU-RRH mapping is studied in [10] using First-Fit-Decreasing algorithm to minimize the number of active BBUs.

This paper differs from previous works in that we propose an energy-efficient approach that considers both RRHs beamforming design and BBUs aggregation to maximize the energy efficiency in heterogeneous C-RAN. Our target is to balance between the achieved rate and the consumed power. The problem is formulated as an optimization problem to maximize the weighted energy efficiency utility function that contains the difference between the achievable rate and the weighted consumed power for both the RRHs beamforming vectors and the active BBUs. Also, we consider BBU processing capability, per-user quality-of-service (QoS) in terms of the achievable rate requirement and per-RRH total transmit power constraints.

The optimization problem is decomposed into two sub problems. The first sub problem is a transmit beamforming vectors optimization problem subject to per-user QoS and per-RRH total transmit power constraints. The users' QoS requirements are converted to a second-order cone (SOC) constraints by applying a phase rotation on the beamforming vectors. Then, the problem is transformed to a weighted sum mean square error (MSE) minimization problem and solved using a weighted minimum mean square error (WMMSE) algorithm. The second sub problem is the BBUs aggregation problem. In this problem, we minimize the number of the active BBUs in the pool by select which RRH should be served by which BBU in the pool under the BBU processing capability constraint. This problem is converted to a bin packing problem and we propose an algorithm based on the Best-Fit-Decreasing method to solve it.

The reminder of this paper is organized as follows: In section II, system model and problem formulation is provided. In section III, the

proposed energy-efficient approach is presented. In section IV, numerical results are provided. Conclusions are presented in section V.

II. SYSTEM MODEL AND PROBLEM FORMULATION

In this section, we present the heterogeneous C-RAN system model with its practical constraints. Also, we formulate the proposed optimization problem.

A. System Model

Suppose that there are M users and N RRHs including two types of RRHs: macro and pico-RRHs. Each user has only single-antenna while each RRH is equipped with L antennas. The baseband processing for all RRHs is performed by the BBU pool that consists of K BBUs. Each RRH is assumed to be connected via high capacity fronthaul link to the BBU pool. Let $\mathcal{M} = \{1, 2, \dots, M\}$, $\mathcal{N} = \{1, 2, \dots, N\}$ and $\mathcal{K} = \{1, 2, \dots, K\}$ denote the sets of users, RRHs and BBUs, respectively. In each BBU, assume that there are S homogenous VMs where each user is served by a VM.

In this paper, we consider joint transmission as a downlink CoMP technique in heterogeneous C-RAN. Let $\mathbf{v}_{nm} \in \mathbb{C}^{L \times 1}$ be the transmit beamforming vector that the RRH n uses to transmit the data symbol $x_m \in \mathbb{C}$ to the user m with the assumption of $\{\mathbb{E}[|x_m|^2] = 1\}$. Then, the received signal \hat{x}_m at user m can be expressed as

$$\hat{x}_m = \sum_{n \in \mathcal{N}} \mathbf{g}_{nm} \mathbf{v}_{nm} x_m + \sum_{i \neq m, i \in \mathcal{M}} \sum_{n \in \mathcal{N}} \mathbf{g}_{ni} \mathbf{v}_{ni} x_i + e_m, \quad (1)$$

where $\mathbf{g}_{nm} \in \mathbb{C}^{1 \times L}$ represents the channel vector from RRH n to user m and $e_m \sim \mathcal{CN}(0, \sigma^2)$ denotes the additive white Gaussian noise (AWGN) at user m . Assuming that the available bandwidth of the wireless channel is B . Then, the achievable rate for user m can be given by

$$R_m = B \log_2 \left(1 + \frac{|\sum_{n \in \mathcal{N}} \mathbf{g}_{nm} \mathbf{v}_{nm}|^2}{\sum_{i \neq m, i \in \mathcal{M}} |\sum_{n \in \mathcal{N}} \mathbf{g}_{ni} \mathbf{v}_{ni}|^2 + \sigma^2} \right). \quad (2)$$

Let us define the binary indicator δ_{mk} to represent whether the user m is served by a VM in BBU k as follows,

$$\delta_{mk} = \begin{cases} 1, & \text{if user } m \text{ is served by BBU } k, \\ 0, & \text{otherwise.} \end{cases} \quad (3)$$

Therefore, the BBU processing capability constraints can be given by

$$\sum_{m \in \mathcal{M}} \delta_{mk} \leq S, \forall k \in \mathcal{K}, \quad (4)$$

where each BBU k can serve only S users. Hence, the BBU pool power consumption can be given by

$$P_{\text{pool}} = \sum_{k \in \mathcal{K}} \rho_k P_{\text{active}}, \quad (5)$$

where P_{active} is the power consumption for the active BBU and ρ_k represents whether BBU k is active or not which can be given by

$$\rho_k = \begin{cases} 0, & \text{if } \sum_{m \in \mathcal{M}} \delta_{mk} = 0, \\ 1, & \text{otherwise.} \end{cases} \quad (6)$$

In addition, the transmit power consumption of each RRH n can be given by

$$P_n^{\text{RRH}} = \sum_{m \in \mathcal{M}} \|\mathbf{v}_{nm}\|_2^2, \quad (7)$$

which is limited to the maximum available transmit power at each RRH n (P_n^{max}).

B. Problem Formulation

In this work, the transmit beamforming vectors design and BBUs aggregation problem is considered to maximize the weighted energy efficiency utility function that contains the difference between the achievable rate and the weighted consumed power for both the RRHs beamforming vectors and the active BBUs. Also, we consider BBU processing capability, per-user QoS in terms of the achievable rate requirement and per-RRH total transmit power constraints. Mathematically, the optimization problem can be formulated as follows,

$$\begin{aligned} (\mathbf{P1}) \quad & \max_{(\mathbf{v}_{nm}, \delta_{mk})} \sum_{m \in \mathcal{M}} UF_m(R_m) \\ & - \alpha \left(\sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}} \|\mathbf{v}_{nm}\|_2^2 \right. \\ & \left. + \sum_{k \in \mathcal{K}} \rho_k P_{\text{active}} \right) \end{aligned} \quad (8)$$

$$s.t. \quad \sum_{m \in \mathcal{M}} \delta_{mk} \leq S, \forall k \in \mathcal{K}, \quad (9)$$

$$\sum_{k \in \mathcal{K}} \delta_{mk} = 1, \forall m \in \mathcal{M}, \quad (10)$$

$$\delta_{mk} \in \{0, 1\}, \forall m \in \mathcal{M}, \forall k \in \mathcal{K}, \quad (11)$$

$$R_m \geq R_m^{\text{req}}, \forall m \in \mathcal{M}, \quad (12)$$

$$\sum_{m \in \mathcal{M}} \|\mathbf{v}_{nm}\|_2^2 \leq P_n^{\text{max}}, \forall n \in \mathcal{N}, \quad (13)$$

where the proportional fairness utility function is chosen, i.e., $UF_m(R_m) = \log(R_m)$, which is widely used in network optimization problems [11]. The parameter α represents the consumed power weight. The constraints in (9) limit the number of served users by each BBU to the maximum number of VMs S in that BBU. The constraints in (10) ensure that each user can only be served by one BBU. While (11) shows that the VMs indicators have binary values. The constraints in (12) represent that each user m has achievable rate requirement R_m^{req} . While (13) ensures the RRH total transmit power limitation.

III. PROPOSED ENERGY-EFFICIENT APPROACH

The weighted energy efficiency utility function can be divided into two sub functions

$$\begin{aligned} F1 = & \sum_{m \in \mathcal{M}} UF_m(R_m) \\ & - \alpha \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}} \|\mathbf{v}_{nm}\|_2^2, \end{aligned} \quad (14)$$

$$F2 = \alpha \sum_{k \in \mathcal{K}} \rho_k P_{\text{active}}, \quad (15)$$

where $F1$ contains the achievable rate utility function and consumed power for the RRHs which are all decided by the transmit beamforming vectors. While $F2$ contains the BBU pool power consumption which obtained based on the BBUs aggregation. According to

these sub functions, the optimization problem (P1) is decomposed into two sub problems. The first sub problem is a transmit beamforming vectors optimization problem subject to per-user QoS and per-RRH total transmit power constraints. While the second sub problem is the BBUs aggregation problem subject to BBU processing capability constraints. The two sub problems solutions are provided in the following subsections.

A. RRHs beamforming design

According to F1 and the constraints related to beamforming vectors design. The first sub problem can be formulated as

$$(P2) \quad \max_{(\mathbf{v}_{nm})} \sum_{m \in \mathcal{M}} UF_m(R_m) - \alpha \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}} \|\mathbf{v}_{nm}\|_2^2 \quad (16)$$

$$s. t. \quad R_m \geq R_m^{\text{req}}, \forall m \in \mathcal{M}, \quad (17)$$

$$\sum_{m \in \mathcal{M}} \|\mathbf{v}_{nm}\|_2^2 \leq P_n^{\text{max}}, \forall n \in \mathcal{N}. \quad (18)$$

It can be observed that the problem (P2) is non-convex due to the interference term in the rate calculation. The users' QoS requirements can be converted to a second-order cone (SOC) constraints by applying a phase rotation on the beamforming vectors without any effect on the formulated optimization problem [11]. Assuming that $\mathbf{g}_{nm}\mathbf{v}_{nm}$ has a positive and real value. Then, the constraints in (17) can be written as follows,

$$\|\mathbf{c}_m\|_2 \leq \sqrt{1 + \frac{1}{\gamma_m} \text{Re}(c_{mm})}, \forall m \in \mathcal{M}, \quad (19)$$

where $\mathbf{c}_m = [\sigma, c_{m1}, \dots, c_{mM}]^T$, $c_{mi} = \sum_{n \in \mathcal{N}} \mathbf{g}_{nm}\mathbf{v}_{ni}$ and $\gamma_m = \left(2^{\frac{R_m^{\text{req}}}{B}} - 1\right)$.

Problem (P2) is still a non-convex optimization problem with respect to the variables \mathbf{v}_{nm} even if the constraints in (17) is replacing by (19). According to [12], this problem can transformed to a weighted sum MSE minimization problem and solved using a WMMSE algorithm.

Since the logarithm utility function in F1 is an increasing function and strictly concave, hence the cost function $Q_m(\cdot) = -UF_m(-\log_2(\cdot))$ is

also strictly concave. Thus, problem (P2) can be transformed to the following minimization problem [12]

$$(P3) \quad \min_{(\mathbf{v}_{nm}, u_m, h_m)} \sum_{m \in \mathcal{M}} \left(h_m \delta_m + Q_m(\beta_m(h_m)) - h_m \beta_m(h_m) \right) + \alpha \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}} \|\mathbf{v}_{nm}\|_2^2 \quad (20)$$

$$s. t. \quad \|\mathbf{c}_m\|_2 \leq \sqrt{1 + \frac{1}{\gamma_m} \text{Re}(c_{mm})}, \quad \forall m \in \mathcal{M}, \quad (21)$$

$$\sum_{m \in \mathcal{M}} \|\mathbf{v}_{nm}\|_2^2 \leq P_n^{\text{max}}, \forall n \in \mathcal{N}, \quad (22)$$

where $u_m \in \mathbb{C}$ denotes the receive beamformer at the user m , h_m is the MSE weight for the user m and $\beta_m(\cdot)$ is the inverse function of the gradient map $\nabla Q_m(\delta_m)$. The variable δ_m denotes the MSE at user m which can be given by

$$\delta_m = E[|u_m^H \hat{x}_m - x_m|^2]. \quad (23)$$

The optimization problem (P3) is convex with respect to each of the optimization variables \mathbf{v}_{nm} , u_m and h_m . Then, we can use block coordinate descent (BCD) method [5] to deal with the problem (P3) with the following steps:

Step 1: The optimal receive beamformer u_m can be obtained under fixed transmit beamforming vector \mathbf{v}_{nm} and MSE weight h_m as follows,

$$u_m = \frac{\sum_{n \in \mathcal{N}} \mathbf{g}_{nm}\mathbf{v}_{nm}}{\sum_{m \in \mathcal{M}} (\sum_{n \in \mathcal{N}} \mathbf{g}_{nm}\mathbf{v}_{nm})(\sum_{n \in \mathcal{N}} \mathbf{v}_{nm}^H \mathbf{g}_{nm}^H) + \sigma^2}, \quad \forall m \in \mathcal{M}. \quad (24)$$

Step 2: Under fixed transmit and receive beamformers \mathbf{v}_{nm} , u_m , the optimal MSE weight h_m can be given by

$$h_m = \nabla Q_m(\delta_m), \forall m \in \mathcal{M}. \quad (25)$$

Step 3: By fixing the receive beamformer u_m and the MSE weight h_m , the optimal transmit beamforming vector \mathbf{v}_{nm} can be found by solving the following quadratically constrained quadratic programming (QCQP) optimization problem.

$$\begin{aligned}
(\text{P4}) \quad & \min_{(\mathbf{v}_{nm})} \sum_{k \in \mathcal{K}} h_m \delta_m \\
& + \alpha \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}} \|\mathbf{v}_{nm}\|_2^2 \quad (26) \\
\text{s. t.} \quad & (21), (22).
\end{aligned}$$

The problem (P4) is convex and can be solved using CVX solver [13]. Algorithm 1 provides the complete steps for the proposed WMMSE algorithm, where φ is a small constant and j_{\max} denotes the maximum iteration number reached.

B. BBUs aggregation solution

Based on F2 and BBU processing capability constraints. The BBUs aggregation problem can be formulated as

$$(\text{P5}) \quad \min_{(\delta_{mk})} \alpha \sum_{k \in \mathcal{K}} \rho_k P_{\text{active}} \quad (27)$$

$$\text{s. t.} \quad \sum_{m \in \mathcal{M}} \delta_{mk} \leq S, \forall k \in \mathcal{K}, \quad (28)$$

$$\sum_{k \in \mathcal{K}} \delta_{mk} = 1, \forall m \in \mathcal{M}, \quad (29)$$

$$\delta_{mk} \in \{0, 1\}, \forall m \in \mathcal{M}, \forall k \in \mathcal{K}. \quad (30)$$

In order to avoid additional computing resources for communication between different BBUs to serve the users in any RRH, all users in one RRH need to be served by one BBU [14]. Let the set of users that are served by the RRH n given by

$$\mathcal{M}_n = \{m | (\|\mathbf{v}_{nm}\|_2^2 \neq 0)\}, \forall n \in \mathcal{N}. \quad (31)$$

Thus, the problem (P5) can be considered as a bin packing problem where the RRHs are treated as items that need to be assigned to a small number of BBUs (bins) to minimize the number of the active BBUs in the pool. This problem has been demonstrated to be a combinatorial NP-hard [15]. We propose an algorithm based on the Best-Fit-Decreasing method to solve this problem. The basic idea of the proposed algorithm is to sort RRHs in a descending order according to the number of users served by each RRH, then try to allocate each RRH in order to the fullest active BBU where it fits in terms of VMs. When there is no active BBU that fulfill the RRH load, turn on a new BBU and assign the RRH to this BBU. Algorithm 2 provides the

Algorithm 1: RRHs beamforming design based on WMMSE algorithm

Initialize: $j = 0, j_{\max}, \varphi, \mathbf{v}_{nm}^{(0)}, \forall n \in \mathcal{N}, \forall m \in \mathcal{M}$.

Repeat:

- 1) Fix $\mathbf{v}_{nm}^{(j)}$, obtain the optimal receive beamformer $\mathbf{u}_m^{(j+1)}$ from (24),
- 2) Given $\mathbf{v}_{nm}^{(j)}$ and $\mathbf{u}_m^{(j+1)}$, obtain the optimal MSE weight $h_m^{(j+1)}$ using (25);
- 3) Solve the problem (P4) to found the optimal transmit beamforming vector $\mathbf{v}_{nm}^{(j+1)}$ under fixed $\mathbf{u}_m^{(j+1)}$ and $h_m^{(j+1)}$;
- 4) $j = j + 1$;

Until $|F1(j) - F1(j-1)| \leq \varphi$, or $j = j_{\max}$.

Algorithm 2: BBUs aggregation solution based on Best-Fit-Decreasing method

Initialize:

Let $S_k = S, \forall k \in \mathcal{K}$.

Sort all RRHs in \mathcal{N} in decreasing order according to $|\mathcal{M}_n|$.

Define the number of active BBU as $K_{\mathcal{A}} = \left\lceil \frac{\sum_{n \in \mathcal{N}} |\mathcal{M}_n|}{S} \right\rceil$.

Define the active BBU set as $\mathcal{K}_{\mathcal{A}} = \{1, 2, \dots, K_{\mathcal{A}}\}$.

Initialize $n = 1$.

Repeat:

- 1) Select RRH n ;
- 2) **if** there is an active BBU k has $S_k - |\mathcal{M}_n| \geq 0$ **then**
- 3) Choose $k^* = \arg \min_k (S_k - |\mathcal{M}_n|), \forall k \in \mathcal{K}_{\mathcal{A}}, \forall k$ have $S_k - |\mathcal{M}_n| \geq 0$;
- 4) Assign all users in the set \mathcal{M}_n to BBU k^* ;
- 5) Let $S_{k^*} = S_{k^*} - |\mathcal{M}_n|$;
- 6) **else**
- 7) Let $k^* = K_{\mathcal{A}} + 1$;
- 8) Assign all users in the set \mathcal{M}_n to BBU k^* ;
- 9) Let $K_{\mathcal{A}} = k^*$ and $S_{k^*} = S_{k^*} - |\mathcal{M}_n|$;
- 10) **end if**
- 11) Let $n = n + 1$;

Until $n = N$.

complete steps for the proposed BBUs aggregation solution.

IV. NUMERICAL RESULTS

In order to show the effectiveness of the proposed energy-efficient approach, simulation results are provided in this section. The proposed

TABLE I. SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
B	10 MHz	α	0.5
σ^2	-174 dBm/Hz	$S_k, \forall k \in \mathcal{K}$	25
φ	0.001	j_{max}	200
P_{active}	100 W [16]	Small scale fast fading	$\mathcal{CN}(0, 1)$
Transmit power of (macro-RRH, pico-RRH)		(46, 30) dBm	
Log-normal shadowing fading		8 dB [17]	
Number of antennas per (macro-RRH, pico-RRH)		(4, 2)	
Path loss between macro-RRH and user m (dB)		$128.1 + 37.6 \log_{10}(d_m)$ [17]	
Path loss between pico-RRH and user m (dB)		$140.7 + 36.7 \log_{10}(d_m)$ [17]	

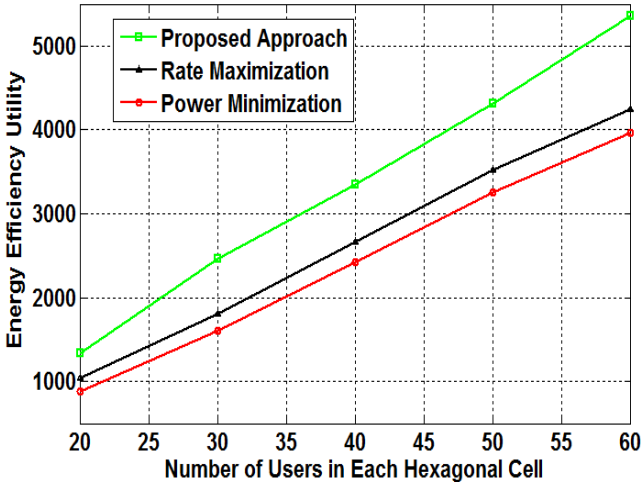


Fig. 1. Energy efficiency utility comparison for different number of users.

approach is compared with two algorithms those consider power minimization [4] and rate maximization [9] objective functions. We consider heterogeneous C-RAN network with 7 macro-RRHs which cover 7 hexagonal cells with radius 500m and 3 pico-RRHs placed at equal distances apart within each hexagonal cell. Users are randomly distributed within the coverage area. The rate requirements for each user has a random value in range [0,10] Mbps. The other simulation parameters are provided in Table I, where d_m is the distance between RRH and user k in kilometres.

Fig. 1 illustrates the value of the weighted energy efficiency utility function versus the number of users in each hexagonal cell for the proposed energy-efficient approach, the "rate maximization" case and the "power

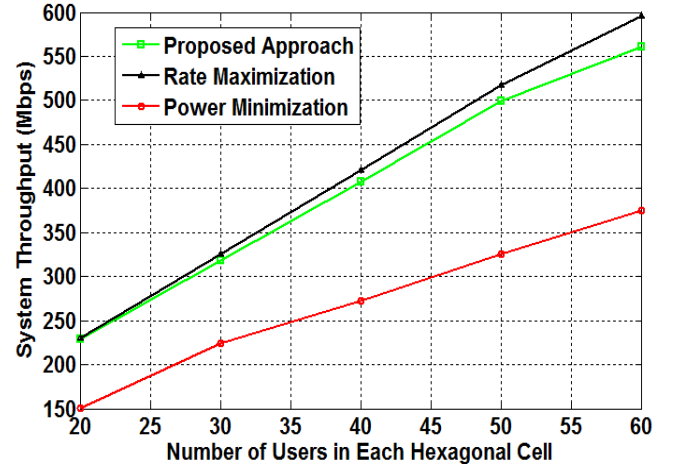


Fig. 2. System throughput comparison for different number of users.

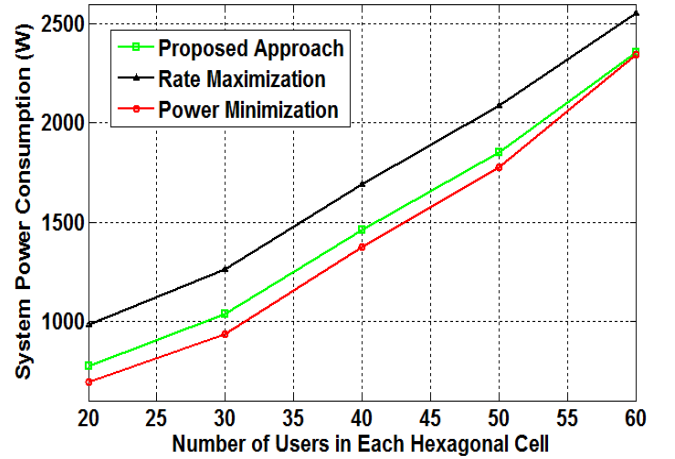


Fig. 3. System power consumption comparison for different number of users.

minimization" case. The results show that, the proposed approach outperforms the previous works in terms of the energy efficiency under different network scenarios. Also, the energy efficiency utility increases when the number of users increases. This is due to the increasing of the achieved rate while the consumed power did not increase much.

Fig. 2 shows the system throughput versus the number of users in each hexagonal cell for all scenarios. It can be seen, the proposed approach outperforms the "power minimization" case. The reason is that, the proposed approach can balance between the achieved rate and the consumed power.

Fig. 3 depicts the system power consumption versus the number of users in each hexagonal cell for all scenarios. It is clear that, the proposed approach outperforms the "rate maximization" case which validates the effectiveness of the proposed algorithm. In addition, the proposed approach can achieve the same performance of

the "power minimization" case at large number of users.

V. CONCLUSION

An energy-efficient approach that considers both RRHs beamforming design and BBUs aggregation problem is studied in this paper for heterogeneous C-RAN. The problem is formulated as an optimization problem and decomposed into two sub problems. The first sub problem is a transmit beamforming vectors optimization problem. This problem is transformed to a weighted sum MSE minimization problem and solved using a WMMSE algorithm. The second sub problem is the BBUs aggregation problem. This problem is converted to a bin packing problem and we propose an algorithm based on the Best-Fit-Decreasing method to solve it. Numerical results show the effectiveness of the proposed energy-efficient approach.

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