Optimal Power Allocation for Distributed MIMO C-RAN System with Limited Fronthaul Capacity

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***Abstract*—This paper investigates the optimal power allocation for the downlink of Multiple-Input Multiple Output (MIMO) Cloud Radio Access Networks (C-RAN) with limited fronthaul capacity in terms of maximizing Energy Efficiency (EE). In the considered system, the compressed and precoded message generated by Central Unit (CU) is transmitted to Remote Radio Heads (RRHs) via a fronthaul link with limited capacity, and the RRHs and Users Equipments (UEs) are assumed to be clustered into S cluster set. Here, we used an iterative algorithm with Lagrangian function to optimize the EE.**

***index Terms*- Coud Radio Access Networks, Multiple-Input Multiple Output, Energy efficincy, Clusterization, Power allocation, Lagrangian function.**

I. Introduction

The growing demand of higher data rates led vendors to think of the next generation of wireless networks which will essentially provide higher throughputs and more coverage than the state-of-art technologies. There are some new concepts introduced to enhance 5G networks such as; Het-Net systems, mmWave communications, Large-scale MIMO systems, and Cloud-Radio Access Networks. Each of the above mentioned concepts fulfills different requirements of 5G networks. As the main focus of this paper is on the C-RAN technology, it is briefly introduced next. In C-RAN systems, in order to have a more efficient system in terms of computational resources, baseband processings, which may have high computational complexities, are transfered from base stations to control centers located in a cloud. In addition to managing computational resources, C-RAN technology can provide new concepts such as co-operation among RRHs, RRH clustering [1], [2]. To obtain both advantages of C-RAN and MIMO system, using MIMO C-RAN system simultaneously can enhance achievable rate and also EE [1]. By using MIMO system, we can achieve higher data rates and even better EE compared to conventional systems by exploiting multiple number of antennas to transmit or receive data streams.

In order to consider feasible links between CU and RRHs, named as *fronthaul*, the capacities of these links are assumed to be limited [3]–[6]. As a result of the limited fronthaul capacity the signals passed through these links need to be compressed [3]–[6] . One of the main problems that recently has attracted the attention of researches in MIMO C-RAN systems is how to efficiently perform detections, precodings and compressions of messages before transmitting them to CU or RRHs. Deploying efficient resource allocations causes prevention of wasting energy and as a result leads to higher EE [1], [2], [7]. In [3]–[6], the authors investigated optimizing

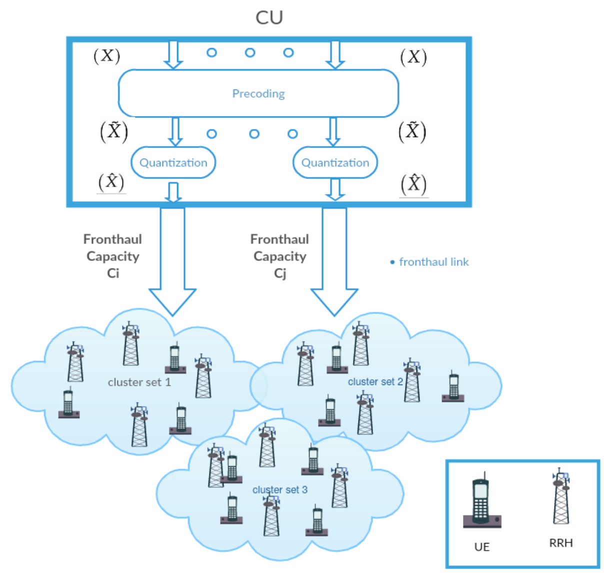

Fig. 1: Cooperative MIMO downlink C-RAN system.

achievable rate according to the precoding and power matrix and quantization noise with fronthaul capacity constraint. In [6], the approach of CFE (Compress-Forward Estimate) in uplink (UL) and improving data rates is investigated by using ECF (Estimate-Compress-Forward) instead can reach better performance in system, where RRH, estimate CSIT in UL, compress message and forward it to CUs studied.

In this paper, the downlink of a MIMO C-RAN system is considered where CU precodes the message, and then compresses the resulting signals. The compressed version of the signal is transmitted over the limited capacity fronthaul links to the RRHs. It is assumed that RRHs and UEs are clustered in a way that several clustered RRHs serve certain groups of UEs. In such a system the knowledge of Channel State Information at Transmitter (CSIT) is needed to compute the precoding matrices. Since CSIT is imperfectly obtained from the uplink pilot transmissions, we assume that the CSIT is obtained with a certain estimation error. At the CU, the well known Minimum Mean Square Error (MMSE) precoding MMSE is applied to reduce multi-user interference and enhance the performance of the system. For the proposed down link system, we firstly derive the achievable rate subject to the fronthaul capacity constraint, then we optimize the power allocation to maxi-

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mize the energy efficiency. The improvement over the equal power allocation is highlighted through numerical discussions. For the proposed down link system, we firstly derive the achievable rate subject to the fronthaul capacity constraint, then we optimize the power allocation to maximize the energy efficiency. The improvement over the equal power allocation is highlighted through numerical discussions.

The paper is organized as follows. System model, achievable rate analysis and problem formulations are presented in Section II. Optimization problems are considered in Section III. Section IV presents numerical results and discussions, and finally the paper is concluded in Section V.

II. System Model and Problem Formulation

In this section, the system model, achievable rate and the main problem which is optimizing power allocation is expressed.

A. System Model

Downlink of a MIMO C-RAN system consists of R RRHs serving D single antenna user equipments (UE) is considered. It is assumed that RRHs and UEs are clustered in to S cluster sets such that the v-th cluster set, has R_v RRHs serving D_v UEs. Furhtermore, it is assumed that the j-th RRH in the v-th cluster is connected to the CU via an optical fiber link with a limited capacity of $c_{r_{(v,j)}}$. So, we have

$$\begin{aligned} \mathcal{R}_v &= \{r_{(v,i)} | 1 \leq i \leq R_v, i \in Z^+\}, \\ \mathcal{C}_{\mathcal{R}_v} &= \{c_{r_{(v,j)}} | 1 \leq j \leq R_v, j \in Z^+\}, \\ \mathcal{D}_v &= \{d_{(v,k)} | 1 \leq k \leq D_v, k \in Z^+\}, \end{aligned} \tag{1}$$

where $\mathcal{R}_v$, $\mathcal{C}_{\mathcal{R}_v}$, and $\mathcal{D}_v$ respectively represent the RRH set, the capacity set and the UE set for the v-th cluster set. In CU we apply the approach of compressing after precoding and then forwarding. Each user receives both intra-cluster and inter-cluster interferences.

B. Achievable Rate Analysis

In this subsection, the achievable data rate of the considered system is investigated.

Theorem 1. *The achievable data rate for UE $d_{(s,k)}$ is*

$$\Re_{d_{(s,k)}} = B \log_2(1 + \gamma_{d_{(s,k)}}), \tag{2}$$

which is obtained by Shannon's theorem, where B is the channel bandwidth and $\gamma_{d_{(s,k)}}$ is the received SINR for the k-th UE in the s-th cluster set which is formulated as

$$\gamma_{d_{(s,k)}} = \frac{p_{d_{(s,k)}} |\boldsymbol{h}^H_{\mathcal{R}_s, d_{(s,k)}} \boldsymbol{w}_{\mathcal{R}_s, d_{(s,k)}}|^2}{I_{d_{(s,k)}} + BN_0}. \tag{3}$$

In (3), *$I_{d_{(s,k)}}$, denotes the power of interfering signals, BN_0 represents the noise power, $\boldsymbol{h}_{\mathcal{R}_s, d_{(s,k)}}$ shows the channel gain vector between the k-th UE and the RRHs in the s-th cluster set, and $\boldsymbol{w}_{\mathcal{R}_s, d_{(s,k)}}$ indicates the precoding vector used in s-th cluster set for the k-th UE. $p_{d_{(s,k)}}$ is the transmit power of RRHs that transmit to the k-th UE in the s-th cluster set.*

Proof. Here, we want to obtain γ which is formulated in theorem (1) .Let $\boldsymbol{y}_{\mathcal{D}_s}$ be a $D_s \times 1$ vector denoting the received signals by the set of UEs in the s-th cluster which is given by

$$\boldsymbol{y}_{\mathcal{D}_s} = \sum_{v=1}^{S} \boldsymbol{H}^H_{\mathcal{R}_v, \mathcal{D}_s} \hat{\boldsymbol{x}}_{\mathcal{R}_v} + \boldsymbol{z}_{\mathcal{D}_s}, \tag{4}$$

where $\hat{\boldsymbol{x}}_{\mathcal{R}_v} = [\hat{x}_{r_{(v,1)}}, ..., \hat{x}_{r_{(v,\mathcal{R}_v)}}]^T \in \mathbb{C}^{R_v}$ is the transmitted symbol vector for the v-th cluster set, $\boldsymbol{z}_{\boldsymbol{\mathcal{D}_s}} \backsim \mathcal{N}(0, N_0 \boldsymbol{I}_{D_s})$ shows the additive White Guassian noise with the power of N_0, and $\boldsymbol{H}_{\mathcal{R}_v, \mathcal{D}_s} = \left[\boldsymbol{h}_{\mathcal{R}_v, d_{(s,1)}}, \ldots, \boldsymbol{h}_{\mathcal{R}_v, d_{(s,\mathcal{D}_s)}}\right]^T \in \mathbb{C}^{R_v \times D_s}$ represents the channel matrix between RRH set $\mathcal{R}_v$ to UE set $\mathcal{D}_s$. The channel vector from the RRH cluster v to the k-th UE in the s-th cluster set $\boldsymbol{h}_{\mathcal{R}_v, d_{(s,k)}} \in \mathbb{C}^{R_v}$ is modeled as follows

$$\boldsymbol{h}_{\mathcal{R}_v, d_{(s,k)}} = \boldsymbol{\beta}^{\frac{1}{2}}_{\mathcal{R}_v, d_{(s,k)}} \boldsymbol{g}_{\mathcal{R}_v, d_{(s,k)}}, \tag{5}$$

where $\boldsymbol{g}_{\mathcal{R}_v, d_{(s,k)}} \backsim \mathcal{N}(0, N_0 \boldsymbol{I}_{\mathcal{D}_s})$ represents the fast and flat fading channel vector and $\boldsymbol{\beta}_{\mathcal{R}_v, d_{(s,k)}} = \mathrm{diag}(a_{r_{(v,1)}, d_{(s,k)}}, \ldots, a_{r_{(v,\mathcal{R}_v)}, d_{(s,k)}})$ indicates the large scale fading matrix [8]. In addition, the transmitted signal has the following form

$$\hat{\boldsymbol{x}}_{\mathcal{R}_v} = \tilde{\boldsymbol{x}}_{\mathcal{R}_v} + \boldsymbol{Q}_{\mathcal{R}_v}, \tag{6}$$

where, $\boldsymbol{Q}_{\mathcal{R}_v} = \left[q_{r_{(v,1)}}, \ldots, q_{r_{(v,R_v)}}\right]^T$, is the quantization noise vector originating from compression made after precoding in the CU with element distribution of $q_{M_{(t,i)}} \backsim \mathcal{N}(0, \sigma^2_{q_{(t,i)}})$. Moreover,

$$\tilde{\boldsymbol{x}}_{\mathcal{R}_v} = \mathbf{W}_{\mathcal{R}_v, \mathcal{D}_v} \mathbf{P}^{\frac{1}{2}}_{\mathcal{D}_v} \boldsymbol{x}_{\mathcal{D}_v},$$

denotes the precoded message before compression.

As mentioned before, channel vector is assumed to be known with errors, the imperfection of channel estimation is modeled as follows

$$\hat{\boldsymbol{h}}_{\mathcal{R}_v, d_{(s,k)}} = \boldsymbol{h}_{\mathcal{R}_v, d_{(s,k)}} + \Delta \boldsymbol{h}_{\mathcal{R}_v, d_{(s,k)}},$$

$\Delta \boldsymbol{h}_{\mathcal{R}_v, d_{(s,k)}}$ denotes the estimation error vector with a Guassian distribution of

$$\Delta \boldsymbol{h}_{\mathcal{R}_v, d_{(s,k)}} \backsim \mathcal{N}(0, \boldsymbol{\phi}^2_{\mathcal{R}_v, d_{(s,k)}}),$$

where

$$\boldsymbol{\phi}_{\mathcal{R}_v, d_{(s,k)}} = \mathrm{diag}(\phi_{r_{(v,1)}, d_{(s,k)}}, \ldots, \phi_{r_{(v,\mathcal{R}_v)}, d_{(s,k)}}).$$

By using MMSE precoding, the precoding matrix is expressed as follows

$$\boldsymbol{W}_{\mathcal{R}_s, \mathcal{D}_s} = \hat{\boldsymbol{H}}_{\mathcal{R}_s, \mathcal{D}_s} (\hat{\boldsymbol{H}}^H_{\mathcal{R}_s, \mathcal{D}_s} \hat{\boldsymbol{H}}_{\mathcal{R}_s, \mathcal{D}_s} + \alpha \boldsymbol{I}_{D_s})^{-1}, \tag{7}$$

where, α is the regularization factor. Therefore, the previously mentioned $I_{d_{(s,k)}}$, denoting the interference power at the

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desired UE in (3), can be written as follows

$$I_{d_{(s,k)}} = \underbrace{\sum_{\substack{l=1\\l\neq k}}^{D_s} |\boldsymbol{h}^H_{\mathcal{R}_s,d_{(s,k)}} \boldsymbol{w}_{\mathcal{R}_s,d_{(s,l)}}|^2 p_{d_{(s,l)}}}_{\text{(intra-cluster interference)}} + \underbrace{\sum_{\substack{v=1\\v\neq s}}^{S} \sum_{l=1}^{D_s} |\boldsymbol{h}^H_{\mathcal{R}_v,d_{(s,k)}} \boldsymbol{w}_{\mathcal{R}_v,d_{(v,l)}}|^2 p_{d_{(v,l)}}}_{\text{(inter-cluster interference)}} + \underbrace{\sum_{v=1}^{S}\sum_{i=1}^{R_v} {\sigma_q}^2_{r_{(v,i)}} \sum_{l=1}^{D_s} |\boldsymbol{h}^H_{r_{(v,i)},d_{(v,l)}}|^2}_{\text{(quantization noise interference)}}. \tag{8}$$

Hence, γ which is signal-to-interference-plus-noise ratio (SINR) can be formulated as

$$\gamma_{d_{(s,k)}} = \frac{p_{d_{(s,k)}} |\boldsymbol{h}^H_{\mathcal{R}_s,d_{(s,k)}} \boldsymbol{w}_{\mathcal{R}_s,d_{(s,k)}}|^2}{I_{d_{(s,k)}} + BN_0}$$

□

III. Optimizing Power Allocation

Let the power of transmitted signal by the i-th RRH in the s-th cluster set by

$$\bar{p}_{r_{(s,i)}} = E[||\hat{x}_{\mathcal{D}_v}||^2], \tag{9}$$

By plugging (6) into (9), the power of transmitted signal is rewritten as

$$\bar{p}_{r_{(s,i)}} = \boldsymbol{w}_{r_{(s,i)},\mathcal{D}_s} \boldsymbol{P}^{\frac{1}{2}}_{\mathcal{D}_v} \boldsymbol{P}^{H\frac{1}{2}}_{\mathcal{D}_v} \boldsymbol{w}^H_{r_{(s,i)},\mathcal{D}_s} + \sigma^2_{q_{(s,i)}}. \tag{10}$$

As a result the achievable rate on the fronthual link between the CU and the i-th RRH in t-th cluster must be larger than

$$C_{R_{(t,i)}} = \log\left(1 + \frac{w_{r_{(s,i)},\mathcal{D}_s} \boldsymbol{P}^{\frac{1}{2}}_{\mathcal{D}_v} \boldsymbol{P}^{H\frac{1}{2}}_{\mathcal{D}_v} w^H_{r_{(s,i)},\mathcal{D}_s}}{\sigma^2_{q_{(s,i)}}}\right), \tag{11}$$

in order to be able to transmit the aforementioned signals via fronthual links.

A. Problem Statement

The ratio of the sum-rate of system to the total power transmitted by RRHs indicates one of the most pormising indicators for selecting new technologies, named as the energy efficiency of system and denoted by η, which can be formulated as

$$\eta(\boldsymbol{P}) := \frac{\sum_{s=1}^{S}\sum_{k=1}^{D_s} \mathfrak{R}_{d_{(s,k)}}}{\sum_{s=1}^{S}\sum_{i=1}^{R_s} \bar{p}_{r_{(s,i)}}} = \frac{R_{total}(\boldsymbol{P})}{P_{RRH}(\boldsymbol{P})}, \tag{12}$$

in which $\boldsymbol{P} = \{\boldsymbol{P}_{\mathcal{D}_s} | 1 \le s \le S, s \in \mathbb{Z}^+\}$ is a power allocation matrix. In this paper, maximization of energy efficiency is investigated with the presence of following constraints,

$$\begin{aligned} \max_{\boldsymbol{P}} \quad & \eta(\boldsymbol{P}) \\ \text{subject to} \quad & \bar{p}_{r_{(s,i)}} \le P_{max} && \forall s, \forall i, \\ & \mathfrak{R}_{d_{(s,k)}} \ge \mathfrak{R}^{th}_{d_{(s,k)}} && \forall s, \forall k, \\ & C_{r_{(s,i)}} \le C^{th}_{r_{(s,i)}} && \forall s, \forall i, \\ & p_{d_{(s,k)}} \ge 0 && \forall s, \forall k, \end{aligned} \tag{13}$$

Since the problem is not a convex problem, an iterative algorithm is used to derive the optimal values for the maximization problem.

B. Proposed Method

In this subsection, instead of maximizing (12), we solve an equivalent problem by using an iterative algorithm.

Theorem 2. *Maximum value of η^* is obtained if and only if*

$$\begin{aligned} &\max_{\boldsymbol{P}}(R_{total}(\boldsymbol{P}) - \eta^* P_{RRH}(\boldsymbol{P})) = \\ &R_{total}(\boldsymbol{P}^*) - \eta^* P_{RRH}(\boldsymbol{P}^*) = 0, \end{aligned} \tag{14}$$

where $\{\boldsymbol{P}\}$ is a feasible solution of problem (13).

Proof. The Theorem is proved using the similar steps as [9, Theorem 1]. □

To solve the optimization problem (14),, we use Lagrangian function by an iterative algorithm proposed in [9]. For simplicity, the upper bound for the interference given in (9), is given by

$$\begin{aligned} \tilde{I}_{d_{(s,k)}} &= \sum_{v=1}^{S} P_{max} ||\boldsymbol{h}_{\mathcal{R}_v,d_{(s,k)}} \boldsymbol{w}_{\mathcal{R}_v,d_{(s,k)}}||^2, \\ &+ \sum_{v=1}^{S}\sum_{i=1}^{R_v} {\sigma_q}^2_{r_{(v,i)}} \sum_{l=1}^{D_s} |\boldsymbol{h}^H_{r_{(v,i)},d_{(v,l)}}|^2. \end{aligned} \tag{15}$$

Therefore, to find the optimal power allocation, the following lower bound is used instead of (2), as

$$\tilde{\mathfrak{R}}_{d_{(s,k)}} = B \log_2(1 + \tilde{\gamma}_{d_{(s,k)}}), \tag{16}$$

where $\tilde{\gamma}_{d_{(s,k)}}$ is

$$\tilde{\gamma}_{d_{(s,k)}} = \frac{p_{d_{(s,k)}} |\boldsymbol{h}^H_{\mathcal{R}_s,d_{(s,k)}} \boldsymbol{w}_{R_s,d_{(s,k)}}|^2}{\tilde{I}_{d_{(s,k)}} + BN_0}; \tag{17}$$

As mentioned before an iterative algorithm is used for optimization which is based on the following Lagrangian

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multiplier function

$$\begin{aligned}\mathcal{L}(\boldsymbol{P};\boldsymbol{\lambda},\boldsymbol{\mu},\boldsymbol{\kappa}) = &\sum_{s=1}^{S}\sum_{k=1}^{\mathcal{D}_s}\tilde{\mathfrak{R}}_{d_{(s,k)}} - \eta\sum_{s=1}^{S}\sum_{i=1}^{\mathcal{R}_s}\bar{p}_{r_{(s,i)}} \\ &+ \sum_{s=1}^{S}\sum_{k=1}^{\mathcal{D}_s}\lambda_{d_{(s,k)}}(\tilde{\mathfrak{R}}_{d_{(s,k)}} - \mathfrak{R}^{th}_{d_{(s,k)}}) \\ &- \sum_{s=1}^{S}\sum_{i=1}^{\mathcal{R}_s}\mu_{r_{(s,i)}}(\bar{p}_{r_{(s,i)}} - P_{max}) \\ &- \sum_{s=1}^{S}\sum_{i=1}^{\mathcal{R}_s}\kappa_{r_{(s,i)}}(C_{r_{(s,i)}} - C^{th}_{r_{(s,i)}}).\end{aligned} \tag{18}$$

where $\boldsymbol{\lambda},\boldsymbol{\mu},\boldsymbol{\kappa} \geq 0$ are Lagrangian multipliers vector [10]. By using this equation, the optimal power allocation is derived as below,

$$p^*_{r_{(s,i)}} = [\frac{B(1+\gamma_{d_{(s,k)}})}{\ln 2 \times (\iota_{r_{(s,i)}} + \chi_{r_{(s,i)}})} - \frac{\tilde{I}_{d_{(s,k)}} + BN_0}{\nu_{d_{(s,k)}}}]^+; \tag{19}$$

where

$$\nu_{d_{(s,k)}} = |h^H_{\mathcal{R}_s,d_{(s,k)}} w_{R_s,d_{(s,k)}}|^2,$$

$$\iota_{r_{(s,i)}} = \sum_{s=1}^{S}\sum_{i=1}^{\mathcal{R}_s}(\mu_{r_{(s,i)}}+1)(w_{r_{(s,i)},d_{(v,l)}} w^*_{r_{(s,i)},d_{(v,l)}}),$$

$$\chi_{r_{(s,i)}} \approx \sum_{s=1}^{S}\sum_{i=1}^{\mathcal{R}_s}\frac{\kappa_{r_{(s,i)}}}{\ln 2}\frac{(w_{r_{(s,i)},d_{(v,l)}} w^*_{r_{(s,i)},d_{(v,l)}})}{\sum_{k=1}^{\mathcal{D}_s} P_{max} + \sigma^2_{q_{r_{(s,i)}}}}.$$

Finally, to find the optimal power allocation, the Algorithm I is applied.

Algorithm 1 Energy-Efficient Power Allocation

1: Set the maximum number of iterations I_{max}, convergence condition ϵ_η and the initial value $\eta^{(1)} = 0$
2: Set the iteration index $i = 1$ and begin the iteration (Outer Loop).
3: **for** $1 \leq i \leq Imax$ **do**
4: Solve the resource allocation problem with $\eta^{(i)}$ (Inner Loop);
5: Obtain $P^{(i)}, R^{(i)}_{total}, P^{(i)}_{RRH}$
6: **if** $R_{total}(\boldsymbol{P}^{(i)}) - \eta^{(i)}P_{RRH}(\boldsymbol{P}^{(i)}) < \epsilon_\eta$ **then**
7: Set $\boldsymbol{P}^* = \boldsymbol{P}^{(i)}$ and $\eta^* = \eta^{(i)}$;
8: break;
9: **else**
10: Set $\eta^{(i)} = \frac{R_{total}(\boldsymbol{P}^{(i)})}{P_{RRH}(\boldsymbol{P}^{(i)})}$ and $i = i+1$;
11: **end if**
12: **end for**

IV. Numerical Results and Discussions

In this section, numerical results of the proposed algorithm are discussed for the MIMO C-RAN system whose parameters are described in Table I.

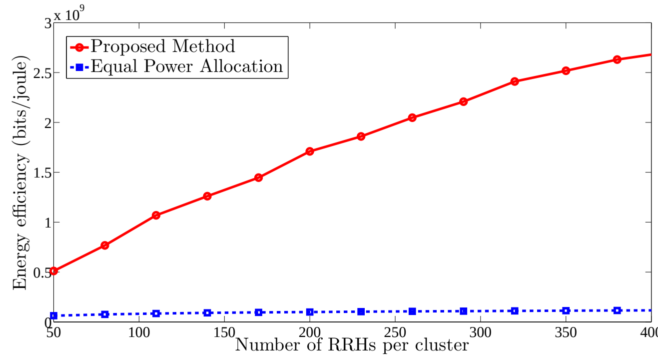

Fig. 2: Energy efficiency vs. number of RRH for optimal and equal power allocation. $U_s = 8$, and the other parameters are given in Table I.

TABLE I: Simulation Parameter

Parameter	Value
Number of cluster S	4
Noise power	-174dBm/Hz
Bandwidth	10MHz
Maxmimun transmit Power	23dBm
Minimum data rate	1Mbits/sec

In Fig. 2, energy efficiency of MIMO C-RAN system with the proposed iterative algorithm and equal power allocations are shown as a function of numbers of RRHs in each cluster. As illustrated, optimal power allocation policy outperforms equal power allocation. In addition, it is shown that the increase in the number of RRHs enhances the performance of system.

In Fig. 3, EE of the proposed iterative algorithm and equal power allocation are depicted for different number of UEs in each cluster. Since by increasing the number of UEs in each cluster, interference is also increased, the system performance is decreased according to the increase in number of UE. It is shown that although the energy efficiency of the considered MIMO C-RAN systems degrades as the number of UEs increases, but still EE of the system using the proposed algorithm surpasses the equal power allocation.

In Fig. 4, EE is depicted as a function of the maximum fronthaul link capacity constraint. It could be understood from the figure that, as the capacity exceeds 12 (bits/s/Hz), the increase in the fronthaul capacity does not affect energy efficiency significantly, since the achievable rate is limited by the wireless channel between RRHs and UEs.

V. Conclusion

The paper has focused on addressing the optimal power allocation in downlink of a MIMO C-RAN system with limited fronthaul capacity. The system model is expressed and the equivalent problem of maximizing the EE is solved by using an iterative algorithm and Lagrangian function. Simulation

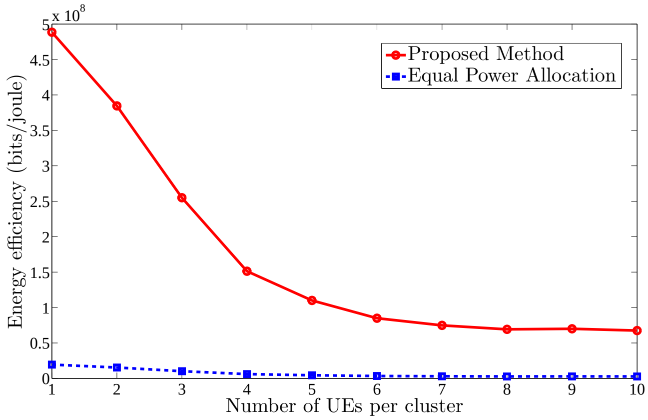

Fig. 3: Energy efficiency vs number of UE for Optimized and Equal Power Allocation, plotted for parameters given in Table I with $M_s = 30$.

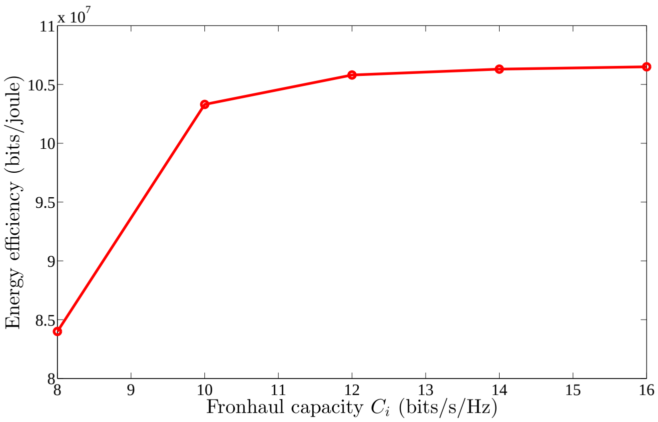

Fig. 4: Energy efficiency vs C^{th} constraint with $S = 3$, $Ms = 20$, $U = 3$.

results demonstrate that the proposed algorithm outperforms the equal power allocation. It is also shown that by increasing the number of RRHs in each cluster, the performance of the system would be enhanced, and increasing the number of UEs in each cluster reduces the system performance.

References

[1] P.-R. Li, T.-S. Chang, and K.-T. Feng, "Energy-efficient power allocation for distributed large-scale mimo cloud radio access networks," in *2014 IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 1856–1861, 2014.

[2] Y.-C. Tsou, P.-R. Li, J.-H. Chu, and K.-T. Feng, "Joint clusterization and power allocation for cloud radio access networks," in *Vehicular Technology Conference (VTC Fall), 2015 IEEE 82nd*, pp. 1–5, 2015.

[3] O. Simeone, J. Kang, J. Kang, and S. Shamai, "Cloud radio access networks: Uplink channel estimation and downlink precoding," *Signal Processing for 5G: Algorithms and Implementations*, pp. 429–455, 2016.

[4] J. Kang, O. Simeone, J. Kang, and S. Shamai, "Joint precoding and fronthaul optimization for c-rans in ergodic fading channels," in *2015 IEEE International Conference on Communication Workshop (ICCW)*, pp. 2683–2688, 2015.

[5] S.-H. Park, O. Simeone, O. Sahin, and S. S. Shitz, "Fronthaul compression for cloud radio access networks: Signal processing advances inspired by network information theory," *IEEE Signal Processing Magazine*, vol. 31, no. 6, pp. 69–79, 2014.

[6] J. Kang, O. Simeone, J. Kang, and S. S. Shitz, "Joint signal and channel state information compression for the backhaul of uplink network mimo systems," *IEEE Transactions on Wireless Communications*, vol. 13, no. 3, pp. 1555–1567, 2014.

[7] C. Yoon and D.-H. Cho, "Energy efficient beamforming and power allocation in dynamic tdd based c-ran system," *IEEE Communications Letters*, vol. 19, no. 10, pp. 1806–1809, 2015.

[8] H. Q. Ngo, A. Ashikhmin, H. Yang, E. G. Larsson, and T. L. Marzetta, "Cell-free massive mimo versus small cells," *arXiv preprint arXiv:1602.08232*, 2016.

[9] M. Peng, K. Zhang, J. Jiang, J. Wang, and W. Wang, "Energy-efficient resource assignment and power allocation in heterogeneous cloud radio access networks," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 11, pp. 5275–5287, 2015.

[10] S. Boyd and L. Vandenberghe, *Convex optimization*. Cambridge university press, 2004.