Energy-Efficient Power Allocation for Distributed Large-Scale MIMO Cloud Radio Access Networks

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***Abstract*—Recently, promoting energy efficiency is an important research issue in the wireless communication system. This paper investigates the resource management problem with the regularized zero-forcing (RZF) precoding for the distributed large-scale multiple-input multiple-output cloud radio access network (DLS MIMO C-RAN) which consists of a large number of spatially distributed remote radio heads (RRHs). The challenges of this power allocation problem arise from the presence of both interference and imperfect channel state information at the transmitter (CSIT). Therefore, the C-RAN based power allocation schemes are designed to efficiently allocate the transmit power of each RRH. Moreover, the large random matrix theory is applied to derive the asymptotic expressions for large number of antennas. Simulation results show that the proposed schemes can provide better energy efficiency with the consideration of quality-of-service (QoS) support.**

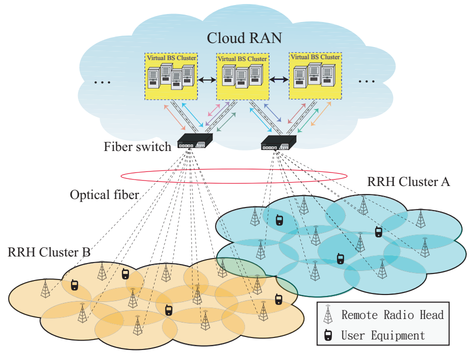

Fig. 1. Network scenario for the DLS MIMO C-RAN.

I. Introduction

Over the past years, the international project, GreenTouch, developed an experimental large-scale antenna system (LSAS) to show that the energy efficiency of wireless communication systems can be significantly improved [1]. Such a system is equipped with a large number of antennas apart from the conventional systems. From theoretical viewpoint, the total transmit power is inversely proportional to the number of transmit antennas [2]. Both the co-located massive MIMO and distributed large-scale (DLS) MIMO networks have been regarded as promising approaches to supply high energy efficiency. The co-located massive MIMO network enjoys a high array gain [2]; while the DLS MIMO system improves energy efficiency by deploying a large number of low-power remote radio heads (RRHs) to boost transmission coverage and provide local throughput enhancement [3].

In order to achieve the advantages of large-scale MIMO systems, it is important to investigate the resource allocation problem. In [4], a joint power, regularization factor of regularized zero-forcing (RZF), and antenna allocation scheme is developed to maximize the spectral efficiency of DLS MIMO systems. However, this approach requires perfect channel state information at the transmitter (CSIT) in the network. In practical environments, imperfect CSIT due to incorrect channel estimation or different feedback rate caused by the mobility of users may influence on the system performance. Apart from the spectral efficiency, the energy efficiency is also viewed as an important performance metric. In [5], considering imperfect CSIT, a joint power, subcarrier, and antenna allocation algorithm was proposed for orthogonal frequency division multiple access (OFDMA) systems with co-located massive antennas.

Motivated by the aforementioned observations, this paper focuses on the DLS MIMO cloud radio access network (C-RAN) in which all the distributed RRHs are connected to the C-RAN via high speed optical fibers [6]. In such a scenario, CSIT are shared among virtual base stations (BSs) as schematically shown in Fig. 1. Intuitively, it would be easier to conduct centralized management in the DLS MIMO C-RAN. However, this type of structure can induce considerable computational loadings which will greatly increase the complexity of management mechanisms. To reduce the complexity incurred in the DLS MIMO C-RAN architecture, all the RRHs can be categorized into different RRH clusters, e.g., Cluster A and Cluster B in Fig.1. Since the RRH clustering is beyond the scope of this paper, the formation of RRH clusters are considered predetermined. In this paper, energy efficiency of the DLS MIMO C-RAN is investigated. The C-RAN-based energy efficient power allocation (CEEPA) scheme is proposed to allocate power under the quality-of-service (QoS) requirement for each UE. Another simplified CEEPA (S-CEEPA) scheme is also proposed to reduce the computational complexity in CEEPA algorithm. Moreover, the deterministic forms of the signal-to-interference-plus-noise (SINR) and RRH transmit power for the DLS MIMO C-RAN are derived. Simulation results validate the accuracy of derived

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asymptotic expressions. It can also be seen that the proposed schemes can provide comparably better energy efficiency.

Notations: Denote bold capital and bold lowercase letters as Matrices and vectors. The Hermitian transpose, trace, two-norm, and Frobenius norm are respectively presented in $(\cdot)^{\mathrm{H}}$, $\mathrm{tr}(\cdot)$, $\|\cdot\|$, and $\|\cdot\|_F$. $\Re\{\cdot\}$ denotes the real part of a complex number. The $n\times n$ identity matrix is symbolized as $\mathbf{I}_n$. $\mathcal{CN}(\mu,\sigma^2)$ means a complex Gaussian random variable with mean μ and variance σ^2, and $\sim$ stands for "distributed as".

II. System Model and Problem Formulation

In this paper, a downlink DLS MIMO C-RAN with U UEs and M RRHs is considered. All the RRHs are clustered into S RRH clusters, i.e., the entire network coverage area is divided into S areas corresponding to the S RRH clusters. Each user is equipped with a single antenna and is only allowed to associate with one RRH cluster. Suppose that RRH cluster s consists of M_s distributed RRHs and serves U_s UEs for all s. Furthermore, $\mathcal{M}_s=\{m_{(s,i)}|1\le i\le M_s, i\in\mathbb{Z}^+\}$ and $\mathcal{U}_s=\{u_{(s,k)}|1\le k\le U_s, k\in\mathbb{Z}^+\}$ denote the RRH set of RRH cluster s and UE set served by RRH cluster s, respectively.

A. System Model

The received signal vector for $\mathcal{U}_s$ can be expressed as

$$\mathbf{y}_{\mathcal{U}_s}=\sum_{t=1}^{S}\mathbf{G}^{\mathrm{H}}_{\mathcal{M}_t,\mathcal{U}_s}\mathbf{W}_{\mathcal{M}_t,\mathcal{U}_t}\mathbf{P}^{1/2}_{\mathcal{U}_t}\mathbf{x}_{\mathcal{U}_t}+\mathbf{z}_{\mathcal{U}_s}, \tag{1}$$

where $\mathbf{x}_{\mathcal{U}_t}=\left[x_{u_{(t,1)}},\cdots,x_{u_{(t,U_t)}}\right]^{\mathrm{T}}$ is the transmit symbol vector of RRH cluster t. $\mathbf{P}_{\mathcal{U}_t}=\mathrm{diag}(p_{u_{(t,1)}},\cdots,p_{u_{(t,U_t)}})$ is a power allocation matrix, where $p_{u_{(t,l)}}$ is the transmit symbol power for UE $u_{(t,l)}$. $\mathbf{z}_{\mathcal{U}_s}\sim\mathcal{CN}(\mathbf{0},N_0\mathbf{I}_{U_s})$ is the white noise, where N_0 represents noise power. $\mathbf{W}_{\mathcal{M}_t,\mathcal{U}_t}=\left[\mathbf{w}_{\mathcal{M}_t,u_{(t,1)}},\cdots,\mathbf{w}_{\mathcal{M}_t,u_{(t,U_t)}}\right]\in\mathbb{C}^{M_t\times U_t}$ is a precoding matrix used by RRH cluster t, and the channel matrix from RRH set $\mathcal{M}_t$ to UE set $\mathcal{U}_s$ is denoted as $\mathbf{G}_{\mathcal{M}_t,\mathcal{U}_s}=\left[\mathbf{g}_{\mathcal{M}_t,u_{(s,1)}},\cdots,\mathbf{g}_{\mathcal{M}_t,u_{(s,U_s)}}\right]\in\mathbb{C}^{M_t\times U_s}$. Note that the channel vector $\mathbf{g}_{\mathcal{M}_t,u_{(s,k)}}\in\mathbb{C}^{M_t}$ from RRH cluster t to UE $u_{(s,k)}$ can be decomposed as

$$\mathbf{g}_{\mathcal{M}_t,u_{(s,k)}}=\mathbf{\Psi}^{1/2}_{\mathcal{M}_t,u_{(s,k)}}\mathbf{h}_{\mathcal{M}_t,u_{(s,k)}}, \tag{2}$$

where $\mathbf{h}_{\mathcal{M}_t,u_{(s,k)}}\sim\mathcal{CN}(\mathbf{0},\mathbf{I}_{M_t})$ denotes fast fading channel vector. $\mathbf{\Psi}_{\mathcal{M}_t,u_{(s,k)}}$ is the large scale fading matrix, which is denoted as $\mathbf{\Psi}_{\mathcal{M}_t,u_{(s,k)}}=\mathrm{diag}(a_{m_{(t,1)},u_{(s,k)}},\cdots,a_{m_{(t,M_t)},u_{(s,k)}})$ where $a_{m_{(t,j)},u_{(s,k)}}$ is the large scale fading factor from j-th RRH of $\mathcal{M}_t$ to k-th UE of $\mathcal{U}_s$.

The transmit power of RRH i in RRH cluster s is equivalent to

$$\bar{p}_{m_{(s,i)}}=\|\mathbf{w}_{m_{(s,i)},\mathcal{U}_s}\mathbf{P}^{1/2}_{\mathcal{U}_s}\|^2, \tag{3}$$

where $\mathbf{w}_{m_{(s,i)},\mathcal{U}_s}$ is the i-th row vector of $\mathbf{W}_{\mathcal{M}_s,\mathcal{U}_s}$.

In general, CSIT is hard to obtain perfectly in practical system due to channel estimation error. To capture this impact of imperfect CSIT, the estimated channel vector $\hat{\mathbf{g}}_{\mathcal{M}_t,u_{(s,k)}}$ is modeled as

$$\hat{\mathbf{g}}_{\mathcal{M}_t,u_{(s,k)}}=\mathbf{g}_{\mathcal{M}_t,u_{(s,k)}}+\Delta\mathbf{g}_{\mathcal{M}_t,u_{(s,k)}}, \tag{4}$$

where $\Delta\mathbf{g}_{\mathcal{M}_t,u_{(s,k)}}$ indicates the estimation error vector. Assuming that a minimum mean square error (MMSE) estimator [7] is employed, $\hat{\mathbf{g}}_{\mathcal{M}_t,u_{(s,k)}}$ and $\Delta\mathbf{g}_{\mathcal{M}_t,u_{(s,k)}}$ will possess Gaussian distribution with zero mean vectors and variance matrices of $\mathbf{\Phi}_{\mathcal{M}_t,u_{(s,k)}}$ and $\mathbf{\Psi}_{\mathcal{M}_t,u_{(s,k)}}-\mathbf{\Phi}_{\mathcal{M}_t,u_{(s,k)}}$ respectively. Note that $\mathbf{\Phi}_{\mathcal{M}_t,u_{(s,k)}}=\mathrm{diag}(\phi_{m_{(t,1)},u_{(s,k)}},\cdots,\phi_{m_{(t,M_t)},u_{(s,k)}})$ where $\phi_{m_{(t,j)},u_{(s,k)}}$ denotes the variance of estimated channel from RRH $m_{(t,j)}$ to UE $u_{(s,k)}$. Invoking the behavior of MMSE estimator, $\hat{\mathbf{g}}_{\mathcal{M}_t,u_{(s,k)}}$ and $\Delta\mathbf{g}_{\mathcal{M}_t,u_{(s,k)}}$ are uncorrelated.

B. Achievable Data Rate with Regularized Zero-forcing Precoding

Assume regularized zero-forcing (RZF) precoding scheme [8] is adopted at the transmitter, the precoding matrix is given by

$$\begin{aligned}\mathbf{W}_{\mathcal{M}_s,\mathcal{U}_s}&=(\hat{\mathbf{G}}_{\mathcal{M}_s,\mathcal{U}_s}\hat{\mathbf{G}}^{\mathrm{H}}_{\mathcal{M}_s,\mathcal{U}_s}+\rho\mathbf{I}_{M_s})^{-1}\hat{\mathbf{G}}_{\mathcal{M}_s,\mathcal{U}_s}\\&=\hat{\mathbf{G}}_{\mathcal{M}_s,\mathcal{U}_s}(\hat{\mathbf{G}}^{\mathrm{H}}_{\mathcal{M}_s,\mathcal{U}_s}\hat{\mathbf{G}}_{\mathcal{M}_s,\mathcal{U}_s}+\rho\mathbf{I}_{U_s})^{-1},\end{aligned} \tag{5}$$

where ρ is a regularization factor. Note that the RZF precoding matrix is calculated according to imperfect CSIT. Although the interference term can be eliminated by adopting RZF precoding scheme, the residual self-interference term due to channel estimation error will result in intra-cluster interference. To this end, base on (1), the received signal for UE $u_{(s,k)}$ can be decomposed as

$$\begin{aligned}y_{u_{(s,k)}}&=\mathbf{g}^{\mathrm{H}}_{\mathcal{M}_s,u_{(s,k)}}\mathbf{w}_{\mathcal{M}_s,u_{(s,k)}}\sqrt{p_{u_{(s,k)}}}x_{u_{(s,k)}}\\&+\sum_{\substack{l=1\\l\neq k}}^{U_s}\underbrace{\mathbf{g}^{\mathrm{H}}_{\mathcal{M}_s,u_{(s,k)}}\mathbf{w}_{\mathcal{M}_s,u_{(s,l)}}\sqrt{p_{u_{(s,l)}}}x_{u_{(s,l)}}}_{\text{Intra-cluster interference}}\\&+\sum_{\substack{t=1\\t\neq s}}^{S}\sum_{l=1}^{U_t}\underbrace{\mathbf{g}^{\mathrm{H}}_{\mathcal{M}_t,u_{(s,k)}}\mathbf{w}_{\mathcal{M}_t,u_{(t,l)}}\sqrt{p_{u_{(t,l)}}}x_{(t,l)}}_{\text{Inter-cluster interference}}+z_{u_{(s,k)}}.\end{aligned} \tag{6}$$

Therefore, the received SINR $\Gamma_{u_{(s,k)}}$ with bandwidth B can be formulated as

$$\Gamma_{u_{(s,k)}}=\frac{p_{u_{(s,k)}}|\,\mathbf{g}^{\mathrm{H}}_{\mathcal{M}_s,u_{(s,k)}}\mathbf{w}_{\mathcal{M}_s,u_{(s,k)}}\,|^2}{I_{u_{(s,k)}}+BN_0}, \tag{7}$$

where $I_{u_{(s,k)}}$ is the interference power which is denoted as

$$\begin{aligned}I_{u_{(s,k)}}&=\sum_{\substack{l=1\\l\neq k}}^{U_s}p_{u_{(s,l)}}|\,\mathbf{g}^{\mathrm{H}}_{\mathcal{M}_s,u_{(s,k)}}\mathbf{w}_{\mathcal{M}_s,u_{(s,l)}}|^2\\&+\sum_{\substack{t=1\\t\neq s}}^{S}\sum_{l=1}^{U_t}p_{u_{(t,l)}}|\,\mathbf{g}^{\mathrm{H}}_{\mathcal{M}_t,u_{(s,k)}}\mathbf{w}_{\mathcal{M}_t,u_{(t,l)}}\,|^2.\end{aligned} \tag{8}$$

As a result, the achievable data rate $R_{u_{(s,k)}}$ of UE $u_{(s,k)}$ can be expressed as

$$R_{u_{(s,k)}} = B\log_2(1+\Gamma_{u_{(s,k)}}). \tag{9}$$

C. Problem Formulation

The network energy efficiency η is defined as the ratio of average total data rate to the total transmit energy consumption which is given by

$$\eta(\mathbf{P}) = \frac{\sum_{s=1}^{S}\sum_{k=1}^{U_s} R_{u_{(s,k)}}(\mathbf{P})}{\sum_{s=1}^{S}\sum_{i=1}^{M_s} \bar{p}_{m_{(s,i)}}(\mathbf{P})}, \tag{10}$$

where $\mathbf{P} = \{\mathbf{P}_{\mathcal{U}_s} | 1 \leq s \leq S, s \in \mathbb{Z}^+\}$ is a power allocation matrices set. In this paper, the main goal is to maximize energy efficiency through power allocation under the constraints of maximum transmit power of each RRH and data rate requirement of each UE. The optimization problem is formulated as follows

$$\begin{aligned} \max_{\mathbf{P}} \quad & \eta(\mathbf{P}) && && \text{(11a)}\\ \text{subject to} \quad & \bar{p}_{m_{(s,i)}} \leq P_{max}, && \forall s, \forall i, && \text{(11b)}\\ & p_{u_{(s,k)}} \geq 0, && \forall s, \forall k, && \text{(11c)}\\ & R_{u_{(s,k)}} \geq R^{\text{th}}_{u_{(s,k)}}, && \forall s, \forall k, && \text{(11d)} \end{aligned}$$

where (11b) is maximum allowed transmit power constraint for each RRH, i.e., P_{max}. By employing the RZF precoding at the transmitter, (3) can be expressed as

$$\bar{p}_{m_{(s,i)}} = \left\| \hat{\mathbf{g}}_{m_{(s,i)},\mathcal{U}_s} (\hat{\mathbf{G}}^{\text{H}}_{\mathcal{M}_s,\mathcal{U}_s} \hat{\mathbf{G}}_{\mathcal{M}_s,\mathcal{U}_s} + \rho \mathbf{I}_{U_s})^{-1} \mathbf{P}^{1/2}_{\mathcal{U}_s} \right\|^2. \tag{12}$$

Constraint (11c) specifies that the power allocation parameters should be greater than or equal to zero. The condition in (11d) indicates that each UE is required to satisfy its target data rate, where the parameter $R^{\text{th}}_{u_{(s,k)}}$ represents the minimum required data rate of UE $u_{(s,k)}$ according to the QoS requirement.

It can be intuitively observed that (11a) and (11d) are non-convex functions with respect to $\mathbf{P}$. Therefore, the optimization problem in (11) is treated as a non-convex problem in which both the intra- and inter-cluster interferences are taken into account.

III. Proposed Power Allocation Schemes

Since the optimization problem in (11) is difficult to solve due to its non-convex property, the following CEEPA and S-CEEPA schemes are proposed to solve the power allocation problem.

A. C-RAN-Based Energy Efficient Power Allocation (CEEPA) Scheme

In this subsection, the CEEPA scheme is proposed to allocate power such that energy efficiency can be maximized. To make the optimization problem (11) easier to solve, the problem is dual decomposed as outer and inner loop problems which are transformed by employing fractional programming (FP) and geometry programming (GP) respectively, and will be discussed as follows.

1) Outer Loop Problem: Intuitively, the objective function (11a) in fractional form is in general nonlinear. By exploiting the FP introduced in [5, Theorem 1], the maximum energy efficiency η^* is defined as

$$\eta^* = \frac{\sum_{s=1}^{S}\sum_{k=1}^{U_s} R_{u_{(s,k)}}(\mathbf{P}^*)}{\sum_{s=1}^{S}\sum_{i=1}^{M_s} \bar{p}_{m_{(s,i)}}(\mathbf{P}^*)} = \max_{\mathbf{P}} \frac{\sum_{s=1}^{S}\sum_{k=1}^{U_s} R_{u_{(s,k)}}(\mathbf{P})}{\sum_{s=1}^{S}\sum_{i=1}^{M_s} \bar{p}_{m_{(s,i)}}(\mathbf{P})}, \tag{13}$$

where $\mathbf{P}^*$ is the optimal power allocation policy. There exists an equivalent subtractive objective function, i.e., $\sum_{s=1}^{S}\sum_{k=1}^{U_s} R_{u_{(s,k)}}(\mathbf{P}) - \eta^* \sum_{s=1}^{S}\sum_{i=1}^{M_s} \bar{p}_{m_{(s,i)}}(\mathbf{P})$. For a given η, (11a) can be rewritten as

$$\max_{\mathbf{P}} \quad \sum_{s=1}^{S}\sum_{k=1}^{U_s} R_{u_{(s,k)}}(\mathbf{P}) - \eta \sum_{s=1}^{S}\sum_{i=1}^{M_s} \bar{p}_{m_{(s,i)}}(\mathbf{P}). \tag{14}$$

As a result, the rest of this paper focuses on the equivalent expression of objective function as in (14).

2) Inner Loop Problem: In this part, the remaining challenge of solving the non-convex inner loop problem is tackled. The GP [9] is applied to convert an original non-convex problem into a concave one by introducing alternative variables. Before applying parameter conversion, a lower bound equation [10] is used and given by

$$\alpha\log\gamma + \beta \leq \log(1+\gamma) \begin{cases} \alpha = \dfrac{\gamma_0}{1+\gamma_0}, \\ \beta = \log(1+\gamma_0) - \dfrac{\gamma_0}{1+\gamma_0}\log\gamma_0. \end{cases} \tag{15}$$

Based on (15), $R_{u_{(s,k)}}$ can be approximated as

$$\hat{R}_{u_{(s,k)}} = B(\alpha_{u_{(s,k)}} \log_2 \Gamma_{u_{(s,k)}} + \beta_{u_{(s,k)}}). \tag{16}$$

After that, we can concave the lower bound term (16) based on the transformation of $\hat{p}_{u_{(s,k)}} = \ln(p_{u_{(s,k)}})$ and rewrite (16) as

$$\begin{aligned} \hat{R}_{u_{(s,k)}} = B\Big(\frac{\alpha_{u_{(s,k)}}}{\ln 2}\big(\ln\big| \mathbf{g}^{\text{H}}_{\mathcal{M}_s,u_{(s,k)}} \mathbf{w}_{\mathcal{M}_s,u_{(s,k)}} \big|^2 \\ + \hat{p}_{u_{(s,k)}} - \ln(I_{u_{(s,k)}} + BN_0)\big) + \beta_{u_{(s,k)}}\Big). \end{aligned} \tag{17}$$

Moreover, (12) is also replaced by

$$\bar{p}_{m_{(s,i)}} = \left\| \hat{\mathbf{g}}_{m_{(s,i)},\mathcal{U}_s} (\hat{\mathbf{G}}^{\text{H}}_{\mathcal{M}_s,\mathcal{U}_s} \hat{\mathbf{G}}_{\mathcal{M}_s,\mathcal{U}_s} + \rho \mathbf{I}_{U_s})^{-1} \hat{\mathbf{P}}^{1/2}_{\mathcal{U}_s} \right\|^2, \tag{18}$$

where $\hat{\mathbf{P}}_{\mathcal{U}_s} = \text{diag}(\exp(\hat{p}_{u_{(s,1)}}), \cdots, \exp(\hat{p}_{u_{(s,U_s)}}))$. Hence, the original optimization problem in (14) can be reformulated as

$$\begin{aligned} \max_{\hat{\mathbf{P}}} \quad & \sum_{s=1}^{S}\sum_{k=1}^{U_s} \hat{R}_{u_{(s,k)}}(\hat{\mathbf{P}}) - \eta \sum_{s=1}^{S}\sum_{i=1}^{M_s} \bar{p}_{m_{(s,i)}}(\hat{\mathbf{P}}) && \text{(19a)}\\ \text{subject to} \quad & \text{(11b), (11c)}, \\ & \hat{R}_{u_{(s,k)}} \geq R^{\text{th}}_{u_{(s,k)}}, \quad \forall s, \forall k. && \text{(19b)} \end{aligned}$$

Algorithm 1: CEEPA Algorithm

Initialize iteration counter $c_1 = 0$ and the maximum number of iterations L_{max}
Initialize the maximum energy efficiency $\eta = 0$ and the maximum tolerance ϖ
repeat
  Set $\alpha^{(0)}_{u_{(s,k)}} = 1$ and $\beta^{(0)}_{u_{(s,k)}} = 0$ (high-SINR approx.)
  Initialize $c_2 = 0$
  repeat
    Maximize: solve the inner loop problem in (19) for a given η to give solution $\hat{\mathbf{P}}^{(c_2)}$
    $\mathbf{P}^{(c_2)} = \exp(\hat{\mathbf{P}}^{(c_2)})$
    Tighten : update $\alpha^{(c_2+1)}_{u_{(s,k)}}$, $\beta^{(c_2+1)}_{u_{(s,k)}}$ with $\mathbf{P}^{(c_2)}$
    increment c_2
  until convergence
  $\mathbf{P}^{(c1)} = \mathbf{P}^{(c2)}$
  if $\sum\limits_{s=1}^{S}\sum\limits_{k=1}^{U_s} R_{u_{(s,k)}}(\mathbf{P}^{(c_1)}) - \eta \sum\limits_{s=1}^{S}\sum\limits_{i=1}^{M_s} \bar{p}_{m_{(s,i)}}(\mathbf{P}^{(c_1)}) < \varpi$ **then**
    converge **= true**
    return $\mathbf{P}^* = \mathbf{P}^{(c_1)}$ and $\eta^* = \sum\limits_{s=1}^{S}\sum\limits_{k=1}^{U_s} R_{u_{(s,k)}}(\mathbf{P}^{(c_1)}) / \sum\limits_{s=1}^{S}\sum\limits_{i=1}^{M_s} \bar{p}_{m_{(s,i)}}(\mathbf{P}^{(c_1)})$
  else
    Set $\eta = \sum\limits_{s=1}^{S}\sum\limits_{k=1}^{U_s} R_{u_{(s,k)}}(\mathbf{P}^{(c_1)}) / \sum\limits_{s=1}^{S}\sum\limits_{i=1}^{M_s} \bar{p}_{m_{(s,i)}}(\mathbf{P}^{(c_1)})$
    increment c_1
    convergence **= false**
  end if
until convergence **= true** or $c_1 = L_{\text{max}}$

where $\hat{\mathbf{P}} = \{\ln(\hat{\mathbf{P}}_{\mathcal{U}_s}) | 1 \le s \le S, s \in \mathbb{Z}^+\}$. Once the solution is acquired, it should be transformed back to the original formulation with $\mathbf{P} = \exp(\hat{\mathbf{P}})$.

The CEEPA scheme deals with the non-linearity and the non-convexity of the optimization problem through FP and GP. Since (11) is transformed into a concave problem, the solution of power allocation matrices set can further be obtained. The detailed procedure for CEEPA scheme is described in Algorithm 1.

B. Simplified C-RAN-Based Energy Efficient Power Allocation (S-CEEPA) Scheme

To further reduce the computational complexity in solving the inner loop problem of CEEPA scheme, a simplified scheme is proposed in this subsection. It is assumed that worst-case interference power model is utilized, namely, all interfering RRHs transmit with maximum power, i.e., P_{max}. Therefore, the precoding vectors are independent of the interfering channels, and the average maximal interference power to UE $u_{(s,k)}$ in RRH cluster s can be formulated as

$$\tilde{I}_{u_{(s,k)}} = \sum_{t=1}^{S} P_{max} \|\mathbf{g}_{\mathcal{M}_t, u_{(s,k)}}\|^2. \tag{20}$$

By substituting $\tilde{I}_{u_{(s,k)}}$ into $I_{u_{(s,k)}}$ in (7), the interference term can be decoupled from the objective function. The original optimization problem (14) can therefore be reformulated as

$$\max_{\mathbf{P}} \quad \sum_{s=1}^{S}\sum_{k=1}^{U_s} \tilde{R}_{u_{(s,k)}}(\mathbf{P}) - \eta \sum_{s=1}^{S}\sum_{i=1}^{M_s} \bar{p}_{m_{(s,i)}}(\mathbf{P}) \tag{21a}$$

$$\text{subject to} \quad (11\text{b}), (11\text{c}),$$

$$\tilde{R}_{u_{(s,k)}} \ge R^{\text{th}}_{u_{(s,k)}}, \quad \forall s, \forall k, \tag{21b}$$

where

$$\tilde{R}_{u_{(s,k)}}(\mathbf{P}) = B\log_2(1 + \tilde{\Gamma}_{u_{(s,k)}}) \;\text{ with }\; \tilde{\Gamma}_{u_{(s,k)}} = \frac{p_{u_{(s,k)}} \varepsilon_{u_{(s,k)}}}{\tilde{I}_{u_{(s,k)}} + BN_0}. \tag{22}$$

Note that $\varepsilon_{u_{(s,k)}} = |\, \mathbf{g}^{\text{H}}_{\mathcal{M}_s, u_{(s,k)}} \mathbf{w}_{\mathcal{M}_s, u_{(s,k)}} |^2$. The objective function and constraints in the transformed problem (21) is now jointly concave with respect to $\mathbf{P}$.

The optimization problem in (21) is solvable by adopting the Lagrangian dual method as follows. The Lagrangian multiplier function can be expressed as

$$\begin{aligned}\mathcal{L}(\mathbf{P}; \boldsymbol{\mu}, \boldsymbol{\lambda}) = & \sum_{s=1}^{S}\sum_{k=1}^{U_s} \tilde{R}_{u_{(s,k)}} - \eta \sum_{s=1}^{S}\sum_{i=1}^{M_s} \bar{p}_{m_{(s,i)}} \\ & - \sum_{s=1}^{S}\sum_{i=1}^{M_s} \mu_{m_{(s,i)}} (\bar{p}_{m_{(s,i)}} - P_{max}) \\ & + \sum_{s=1}^{S}\sum_{k=1}^{U_s} \lambda_{u_{(s,k)}} (\tilde{R}_{u_{(s,k)}} - R^{\text{th}}_{u_{(s,k)}}),\end{aligned} \tag{23}$$

where $\boldsymbol{\mu}$ and $\boldsymbol{\lambda}$ are the sets of all Lagrangian multipliers associated with the power constraint and the required minimum data rate constraint with elements $\mu_{m_{(s,i)}} \ge 0$ and $\lambda_{u_{(s,k)}} \ge 0$, respectively. According to standard optimization techniques and the KKT conditions, the sub-optimal power allocation for UE $u_{(s,k)}$ in the RRH cluster s is obtained as

$$p^*_{u_{(s,k)}} = \left[\frac{B(1 + \lambda_{u_{(s,k)}})}{(\ln 2)\zeta_{u_{(s,k)}}} - \frac{\tilde{I}_{u_{(s,k)}} + BN_0}{\varepsilon_{u_{(s,k)}}} \right]^+, \tag{24}$$

where $\zeta_{u_{(s,k)}} = (\eta \|\mathbf{w}_{\mathcal{M}_s, u_{(s,k)}}\|^2 + \sum\limits_{i=1}^{M_s} \mu_{m_{(s,i)}} |w_{m_{(s,i)}, u_{(s,k)}}|^2)$. To this end, the closed form expression of power allocation is derived in the proposed S-CEEPA scheme.

IV. Asymptotic Expressions for Optimization Objective and Constraints

In frequency division duplex (FDD) systems, the overheads from both CSI feedback and signaling that are related to channel training grow with the numbers of transmit antennas and UEs. For the sake of reducing the overhead incurred in FDD system, this paper introduces the following asymptotic approximations by taking the advantages of a large number of RRHs, which can further filter out the effect of fast fading. Before conducting asymptotic derivation, the following assumption is required.

Assumption 1. *The elements of large scale fading matrices are bounded, i.e.,*

$$\limsup_{M_t} \|\mathbf{\Psi}_{\mathcal{M}_t, u_{(s,k)}}\| < \infty, \quad \forall s, \forall t, \forall k \tag{25}$$

$$\liminf_{M_t} \frac{1}{M_t} \mathrm{tr}(\mathbf{\Psi}_{\mathcal{M}_t, u_{(s,k)}}) > 0, \quad \forall s, \forall t, \forall k \tag{26}$$

In the sequel, the following two lemmas provide deterministic approximations of SINR in (7) and RRH transmit power in (12) under Assumption 1 in large system limit when $M_s, U_s \to \infty$ with $\lim_{M_s \to \infty} M_s/U_s = \chi \in (0, \infty)$.

Lemma 1. (Deterministic approximation for the SINR) *Under* Assumption 1, $\Gamma_{u_{(s,k)}} - \bar{\Gamma}^{ASY}_{u_{(s,k)}} \underset{M_s \to \infty}{\longrightarrow} 0$ *hold almost surely, where the asymptotic expression of SINR is derived as*

$$\bar{\Gamma}^{ASY}_{u_{(s,k)}} = \frac{p_{u_{(s,k)}} \delta^2_{\mathcal{M}_s, u_{(s,k)}}}{(\bar{I}^{ASY}_{u_{(s,k)}} + BN_0)(1 + \delta_{\mathcal{M}_s, u_{(s,k)}})^2} \tag{27}$$

with the interference power $\bar{I}^{ASY}_{s,u_s}$ which is written as

$$\bar{I}^{\mathrm{ASY}}_{u_{(s,k)}} = \sum_{\substack{l=1 \\ l \neq k}}^{U_s} \frac{p_{u_{(s,l)}} \xi_{\mathcal{M}_s, u_{(s,k)}, u_{(s,l)}}}{M_s(1 + \delta_{\mathcal{M}_s, u_{(s,l)}})^2} + \sum_{\substack{t=1 \\ t \neq s}}^{S} \sum_{l=1}^{U_t} \frac{p_{u_{(t,l)}} \xi_{\mathcal{M}_t, u_{(s,k)}, u_{(t,l)}}}{M_s(1 + \delta_{\mathcal{M}_t, u_{(t,l)}})^2} \tag{28}$$

where

$$\delta_{\mathcal{M}_t, u_{(t,l)}} = \frac{1}{M_t} \mathrm{tr} \mathbf{\Phi}_{\mathcal{M}_t, u_{(s,k)}} \mathbf{T}_t \tag{29}$$

$$\varphi_{\mathcal{M}_t, u_{(s,k)}} = \frac{1}{M_t} \mathrm{tr} \mathbf{\Phi}_{\mathcal{M}_t, u_{(s,k)}} \mathbf{T}_t \tag{30}$$

$$\varphi'_{\mathcal{M}_t, u_{(s,k)}, u_{(t,l)}} = \frac{1}{M_t} \mathrm{tr} \mathbf{\Phi}_{\mathcal{M}_t, u_{(s,k)}} \mathbf{T}'_{t, u_{(t,l)}} \tag{31}$$

$$\begin{aligned} \xi_{\mathcal{M}_t, u_{(s,k)}, u_{(t,l)}} &= \frac{1}{M_t} \mathrm{tr} \mathbf{\Psi}_{\mathcal{M}_t, u_{(s,k)}} \mathbf{T}'_{t, u_{(t,l)}} \\ &\quad - \frac{2\Re\{\varphi^*_{\mathcal{M}_t, u_{(s,k)}} \varphi'_{\mathcal{M}_t, u_{(s,k)}, u_{(t,l)}}\}(1 + \delta_{\mathcal{M}_t, u_{(t,l)}})}{(1 + \delta_{\mathcal{M}_t, u_{(t,l)}})^2} \\ &\quad + \frac{|\varphi_{\mathcal{M}_t, u_{(s,k)}}|^2 \delta'_{\mathcal{M}_t, u_{(s,k)}, u_{(t,l)}}}{(1 + \delta_{\mathcal{M}_t, u_{(t,l)}})^2} \end{aligned} \tag{32}$$

The parameters $\boldsymbol{\delta}_{\mathcal{M}_t} = \left[\delta_{\mathcal{M}_t, u_{(t,1)}}, \cdots, \delta_{\mathcal{M}_t, u_{(t,U_t)}}\right]^{\mathrm{T}} = \boldsymbol{\delta}(\rho/M_t)$, $\mathbf{T}_t = \mathbf{T}(\rho/M_t)$, *and* $\mathbf{T}'_{t,u_{(t,l)}} = \mathbf{T}'(\rho/M_t)$ *are given by [11, Theorem 1,2]. The derivations of desired signal power and interference power in* (27) *are proved in [11].*

Lemma 2. (Deterministic approximation for RRH transmit power) *Under* Assumption 1, $\bar{p}_{m_{(s,i)}} - \bar{p}^{ASY}_{m_{(s,i)}} \underset{M_s \to \infty}{\longrightarrow} 0$ *hold almost surely, where the asymptotic expression of RRH transmit power is derived as*

$$\bar{p}^{ASY}_{m_{(s,i)}} = \left|\frac{\bar{\vartheta}_{m_{(s,i)}, \mathcal{U}_s}}{U_s(1 + \bar{\delta}_{m_{(s,i)}, \mathcal{U}_s})^2}\right|^2 \tag{33}$$

TABLE I
MAIN SYSTEM PARAMETERS

Parameter	Value
Number of clusters S	4
System bandwidth B	10 MHz
Carrier frequency	2 GHz
Noise power N_0	-174 dBm
Maximum transmit power per RRH P_{max}	23 dBm
Regularization factor ρ	0.1
Minimum data rate requirement	1 Mbits/sec

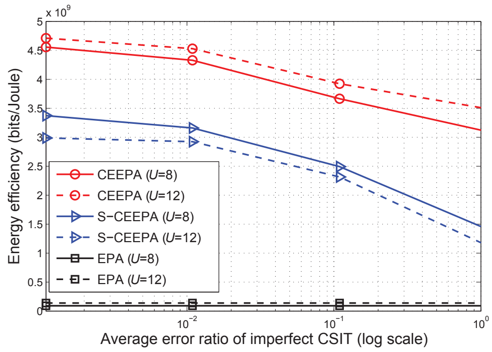

Fig. 2. Performance comparison between EPA method and proposed schemes: energy efficiency versus average error ratio of imperfect CSIT under $U = 8, 12$ and $M_s = 36$.

where

$$\bar{\delta}_{m_{(s,i)}, \mathcal{U}_s} = \frac{1}{U_s} \mathrm{tr} \mathbf{\Phi}_{m_{(s,i)}, \mathcal{U}_s} \bar{\mathbf{T}}_s \tag{34}$$

$$\bar{\vartheta}_{m_{(s,i)}, \mathcal{U}_s} = \frac{1}{U_s} \mathrm{tr} \mathbf{\Phi}_{m_{(s,i)}, \mathcal{U}_s} \bar{\mathbf{T}}'_{s, m_{(s,k)}} \tag{35}$$

The parameters $\bar{\boldsymbol{\delta}}_{\mathcal{U}_s} = \left[\bar{\delta}_{m_{(s,1)}, \mathcal{U}_s}, \cdots, \bar{\delta}_{m_{(s,M_s)}, \mathcal{U}_s}\right] = \boldsymbol{\delta}(\rho/U_s)$, $\bar{\mathbf{T}}_s = \mathbf{T}(\rho/U_s)$, *and* $\bar{\mathbf{T}}'_{s,m_{(s,k)}} = \mathbf{T}'(\rho/U_s)$ *are given by [11, Theorem 1,2] for* $\mathbf{\Theta} = \mathbf{P}_{\mathcal{U}_s}$, $\mathbf{D} = \mathbf{I}_{U_s}$, *and* $\mathbf{R}_k = \mathbf{\Phi}_{m_{(s,i)}, \mathcal{U}_s}$. *The derivation is similar to Lemma 1. Note that* $\mathbf{\Phi}_{m_{(s,i)}, \mathcal{U}_s} = \mathrm{diag}(\phi_{m_{(s,i)}, u_{(s,1)}}, \cdots, \phi_{m_{(s,i)}, u_{(s,U_s)}})$.

Afterwards, we can apply the deterministic approximations of SINR and the RRH transmit power in substitution for original objective and constraints in (11), which can consequently be solved by the proposed CEEPA and S-CEEPA schemes.

V. PERFORMANCE EVALUATION

In this section, simulation results are provided. Consider the DLS MIMO C-RAN system with a square coverage area of 0.5 km$\times$0.5 km. The grid distributed RRHs are equally grouped into four RRH clusters based on geolocation. It is assumed that the imperfect CSIT error variance between each UE and RRH is equal and specified, i.e., $\mathbf{\Psi}_{\mathcal{M}_s, u_{(s,k)}} - \mathbf{\Phi}_{\mathcal{M}_s, u_{(s,k)}} = c\mathbf{I}_{U_s}$ for all s and k, where c is a constant. The error ratio of imperfect CSIT is defined as the average value of $\|\mathbf{\Psi}_{\mathcal{M}_s, u_{(s,k)}} - \mathbf{\Phi}_{\mathcal{M}_s, u_{(s,k)}}\|_F / \|\mathbf{\Psi}_{\mathcal{M}_s, u_{(s,k)}}\|_F$. Moreover, the channel model used for simulation is referred to [12]. The main system parameters are listed in Table I.

In Fig. 2, the energy efficiency of proposed schemes and the equal power allocation (EPA) scheme versus the average error

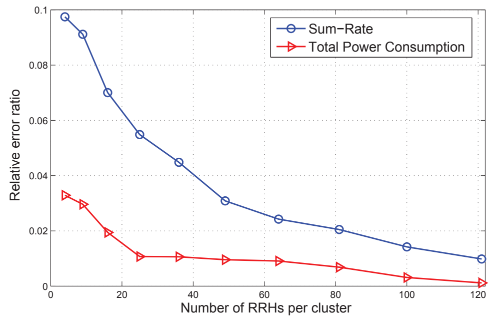

Fig. 3. Relative error ratios of approximated sum-rate and approximated total power consumption versus number of RRHs per RRH cluster under $U = 8$.

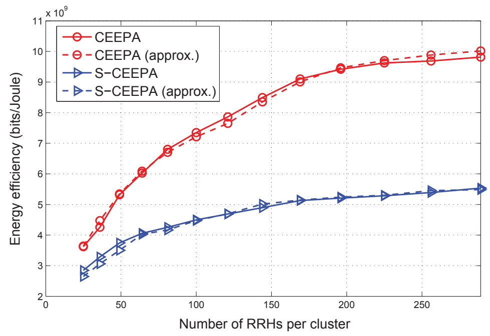

Fig. 4. Performance comparison between asymptotic results and simulation results: energy efficiency versus number of RRHs per RRH cluster under $U = 8$.

ratio of imperfect CSIT is plotted for $U = 8, 12$ and $M_s = 36$. The EPA scheme is designed to equally and maximally allocate the transmit power of each RRH, i.e., P_{max}. It can be seen that the proposed schemes can provide comparably better energy efficiency than EPA scheme due to their advanced power allocation procedures. It can also be observed that the CEEPA scheme can provide higher energy efficiency compared to the S-CEEPA scheme since the CEEPA scheme allocate power with the consideration of more realistic interference than the S-CEEPA scheme. Fig. 2 also draws the benefit of multi-user diversity gain for the CEEPA scheme, i.e., the case with $U = 12$ versus that with $U = 8$.

In order to verify the accuracy of deterministic approximations (27) and (33), the relative error ratio is adopted as the performance metric. The relative error ratio of sum-rate is define as $|R_{sum} - R_{sum}^{ASY}|/R_{sum}$, where R_{sum} and R_{sum}^{ASY} are the achievable sum-rate in (10) and the approximated sum-rate respectively. The relative error ratio of total power consumption is defined in the similar manner. Fig. 3 illustrates the relative error ratios of approximated sum-rate and approximated total power consumption versus the number of RRHs per RRH cluster under $U = 8$. For the sake of fairness, equal symbol power is assumed, i.e., the same value is given to the elements of power allocation matrix in (1). Clearly, the deterministic approximations approach to the simulation results and the relative error ratios decrease as the number of RRHs increases.

For numerical analyses, the following additional design criteria have been considered: CEEPA and S-CEEPA schemes with asymptotic expressions of SINR and RRH transmit power. Fig. 4 depicts the energy efficiency of considered schemes versus the number of RRHs per RRH cluster under $U = 8$. It can be observed that the asymptotic regimes are very close to the proposed schemes, which justify the accuracy of deterministic approximations. The merits of proposed schemes can therefore be observed.

VI. Conclusions

In this paper, an energy efficient distributed large-scale MIMO cloud radio access network (DLS MIMO C-RAN) is considered with the imperfect channel state information at the transmitter (CSIT) and the presence of intra-cluster and inter-cluster interferences. Both the C-RAN-based energy efficient power allocation (CEEPA) scheme and the simplified C-RAN-based energy efficient power allocation (S-CEEPA) scheme are proposed to efficiently allocate power under the quality-of-service (QoS) constraints for all UEs. Moreover, the large random matrix theorem is utilized to derive the asymptotic approximations of signal-to-interference-plus-noise (SINR) and remote radio head (RRH) transmit power. Simulation results show that the proposed schemes can provide better energy efficiency, and the accuracy of derived asymptotic expressions are verified.

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