COORDINATED DOWNLINK AND UPLINK USER ASSOCIATION AND BEAMFORMING FOR ENERGY MINIMIZATION IN CLOUD RADIO ACCESS NETWORK

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ABSTRACT

Cloud radio access network (C-RAN) has been recently proposed, in which densely deployed access points (APs) are empowered by cloud computing, to achieve enormous mobile data rates. However, close proximity of many active APs results in more severe interference and also inefficient energy consumption. To tackle this problem, we propose a joint downlink (DL) and uplink (UL) user-AP association and beamforming design in this paper to coordinate interference in the C-RAN for energy minimization. The design problem is shown to be NP hard, but exhibits an interesting "group-sparse" property. By establishing a virtual DL transmission for the original UL transmission based on the celebrated UL-DL duality result, we convert the problem to an equivalent DL problem in C-RAN with two inter-related subproblems for the original and virtual DL transmissions, respectively, and obtain an efficient solution through "group-sparse" optimization.

1. INTRODUCTION

To meet the fast growing mobile data volume driven by applications such as smartphones and tablets, traditional wireless network architecture based on macro-cells has shifted to the one composed of smaller cells such as pico/femto cells with more densely deployed access points (APs). Therefore, cloud radio access network (C-RAN) [1] has recently been proposed and drawn a great deal of attention. In a C-RAN, the APs, also termed remote radio heads (RRHs), are connected to the baseband unit (BBU) pool through high bandwidth backhaul links to enable centralized processing, collaborative transmission, and real-time cloud computing. However, with densely deployed APs, several new challenges arise in C-RAN. First, close proximity of many active APs results in more severe interference across different cells and hence the transmit power of APs and/or mobile users (MUs) needs to be increased to meet the given transmission quality of service (QoS). Second, the amount of energy consumed by a large number of active APs due to their operational units such as air-conditioners [2] as well as radio transmissions also becomes considerable.

To tackle the interference and/or energy inefficiency issues in wireless networks, many solutions have been proposed in the literature, such as dynamic resource allocation [3–5], load balancing [6,7], AP "on/off" control [8,9], and coordinated multi-point (CoMP) transmission [10]. Among others, joint MU association and active AP selection [11–13] is one promising solution, which minimizes the adverse effects of interference in the network by optimally assigning MUs to be served by the minimal subset of "on" APs so as to reduce the network's total energy consumption. However, prior studies [11–13] have all considered MU association and/or active AP selection problems from the downlink (DL) transmission perspective, which may result in inefficient transmit power of MUs or even power infeasibility in the uplink (UL) transmission considering various possible asymmetries between the DL and UL in terms of channel, traffic and hardware limitation.

In this paper, we consider a C-RAN consisting of densely deployed APs jointly serving a set of distributed MUs, where CoMP based joint transmit/receive processing (beamforming) over all active APs is assumed for DL/UL transmissions. Under this setup, we study a joint DL and UL user-AP association and beamforming (UABF) problem to minimize the total energy consumption in the network subject to MUs' given UL and DL QoS requirements. The problem involves integer programming and thus is NP hard. However, the solution of the problem is shown to exhibit an interesting "group-sparse" property, similar to that considered in [12–15], as only a small fraction of the total number of APs needs to be "on" for meeting the MUs' QoS thanks to the high AP deployment density. By establishing a virtual DL transmission for the original UL transmission in C-RAN based on the celebrated UL-DL duality result [16], which is shown to be essential to overcome a scaling issue in the UL receive beamforming design, we transform the joint UL and DL UABF problem in C-RAN to an equivalent DL problem with two inter-related subproblems corresponding to the original and virtual DL transmissions, respectively, and thereby obtain an efficient solution by utilizing "group-sparse" optimization techniques [18]. Finally, numerical results are provided to demonstrate the performance of the proposed algorithm.

2. SYSTEM MODEL

We consider a densely deployed C-RAN consisting of N APs denoted by the set $\mathcal{N} = \{1, \cdots, N\}$, which jointly support DL and UL communications with K randomly located MUs, denoted by the set $\mathcal{K} = \{1, \cdots, K\}$. We assume that each AP n, $n \in \mathcal{N}$, is equipped with $M_n \geq 1$ antennas, and all MUs are each equipped with one antenna. Let $\sum_{n=1}^{N} M_n = M$. It is also assumed that there exist low-latency high-speed backhaul links connecting the set of APs to the BBU pool, which performs all the baseband signal processing and transmission scheduling for all APs.

We consider a quasi-static fading environment, and denote the channel vector in the DL from AP n to MU i as $\mathbf{h}_{i,n}^H \in \mathbb{C}^{1\times M_n}$. Let the vector consisting of the channels from all the APs to MU i be $\mathbf{h}_i^H = \left[\mathbf{h}_{i,1}^H, \cdots, \mathbf{h}_{i,N}^H\right]$. We assume time-division duplex (TDD) in this paper for simplicity, such that channel reciprocity holds for UL and DL transmissions. Therefore, the channel vector in the UL is merely the transpose of that in the DL. It is further assumed that the BBU pool knows all the channel $\mathbf{h}_i$'s.

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2.1. DL Transmission

In DL transmission, the transmitted signal from all APs is given by

$$\mathbf{x}^{\text{DL}} = \sum_{i=1}^{K} \mathbf{w}_i^{\text{DL}} s_i^{\text{DL}} \tag{1}$$

where $\mathbf{w}_i^{\text{DL}} \in \mathbb{C}^{M\times 1}$ is the beamforming vector for all APs to cooperatively send one single stream of data signal s_i^{DL} to MU i, which is assumed to be a circularly symmetric complex random variable with zero mean and unit variance.

The received signal at the ith MU is then expressed as

$$y_i^{\text{DL}} = \mathbf{h}_i^H \mathbf{w}_i^{\text{DL}} s_i^{\text{DL}} + \sum_{j\neq i}^{K} \mathbf{h}_i^H \mathbf{w}_j^{\text{DL}} s_j^{\text{DL}} + z_i^{\text{DL}}, \;\; i = 1, \cdots, K \tag{2}$$

where z_i^{DL} is the receiver noise at MU i, which is assumed to be a circularly symmetric complex Gaussian (CSCG) random variable with zero mean and variance σ^2, denoted by $z_i^{\text{DL}} \sim \mathcal{CN}(0, \sigma^2)$. Treating the interference as noise, the signal-to-interference-plus-noise ratio (SINR) in DL for MU i is given by

$$\text{SINR}_i^{\text{DL}} = \frac{|\mathbf{h}_i^H \mathbf{w}_i^{\text{DL}}|^2}{\sum_{j\neq i} |\mathbf{h}_i^H \mathbf{w}_j^{\text{DL}}|^2 + \sigma^2}, \;\; i = 1, \cdots, K. \tag{3}$$

2.2. UL Transmission

In UL transmission, the transmitted signal from MU i is given by

$$x_i^{\text{UL}} = \sqrt{p_i^{\text{UL}}} s_i^{\text{UL}}, \;\; i = 1, \cdots, K \tag{4}$$

where p_i^{UL} denotes the transmit power of MU i, and s_i^{UL} is the information bearing signal which is assumed to be a circularly symmetric complex random variable with zero mean and unit variance.

The received signal at all APs is then expressed as

$$\mathbf{y}^{\text{UL}} = \sum_{i=1}^{K} \mathbf{h}_i^* \sqrt{p_i^{\text{UL}}} s_i^{\text{UL}} + \mathbf{z}^{\text{UL}} \tag{5}$$

where $\mathbf{z}^{\text{UL}} \in \mathbb{C}^{M\times 1}$ denotes the receiver noise vector at all APs consisting of independent CSCG random variables each distributed as $\mathcal{CN}\left(0, \sigma^2\right)$. Let $\mathbf{v}_i^{\text{UL}} \in \mathbb{C}^{M\times 1}$ denote the receiver beamforming vector used to decode s_i^{UL} from MU i. Then the SINR in UL for MU i after applying $\mathbf{v}_i^{\text{UL}}$ is given by

$$\text{SINR}_i^{\text{UL}} = \frac{p_i^{\text{UL}} |(\mathbf{v}_i^{\text{UL}})^T \mathbf{h}_i^*|^2}{\sum_{j\neq i} p_j^{\text{UL}} |(\mathbf{v}_i^{\text{UL}})^T \mathbf{h}_j^*|^2 + \sigma^2 \|\mathbf{v}_i^{\text{UL}}\|^2}, \;\; i = 1, \cdots, K. \tag{6}$$

2.3. Energy Consumption Model

The total network energy consumption comprises of the energy consumed by all APs and that by all MUs. From (1) and (4), the total transmit power of all APs in DL and that from all MUs in UL can be expressed as $P_t^{\text{DL}} = \sum_{i=1}^{K} \|\mathbf{w}_i^{\text{DL}}\|^2$ and $P_t^{\text{UL}} = \sum_{i=1}^{K} p_i^{\text{UL}}$, respectively.

Moreover, we consider that for energy saving, some APs can be switched off; thus, the static power consumption of AP n denoted by $P_{c,n}$, $n \in \mathcal{N}$, can be saved if AP n is switched off for both transmission in DL and reception in UL. For convenience, we express the total static power consumption of all "on" APs as

$$P_c = \sum_{n=1}^{N} \mathbf{1}_n \left(\{\mathbf{w}_{i,n}^{\text{DL}}\}, \{\mathbf{v}_{i,n}^{\text{UL}}\} \right) P_{c,n} \tag{7}$$

where $\mathbf{w}_{i,n}^{\text{DL}} \in \mathbb{C}^{M_n\times 1}$ and $\mathbf{v}_{i,n}^{\text{UL}} \in \mathbb{C}^{M_n\times 1}$ are the nth block component in $\mathbf{w}_i^{\text{DL}}$ and $\mathbf{v}_i^{\text{UL}}$, respectively, corresponding to transmit/receive beamforming vectors at AP n for MU i. $\mathbf{1}_n(\cdot)$, $n \in \mathcal{N}$, is an indicator function for AP n, which is defined as

$$\mathbf{1}_n \left(\{\mathbf{w}_{i,n}^{\text{DL}}\}, \{\mathbf{v}_{i,n}^{\text{UL}}\} \right) = \begin{cases} 0 & \text{if } \mathbf{w}_{i,n}^{\text{DL}} = \mathbf{v}_{i,n}^{\text{UL}} = \mathbf{0}, \forall i \in \mathcal{K} \\ 1 & \text{otherwise.} \end{cases} \tag{8}$$

We aim to minimize the total energy consumption in the C-RAN, including that due to transmit power of all MUs as well as that due to transmit power and static power of all "on" APs. Therefore, we consider the following weighted sum-power as our design metric:

$$P_{\text{total}} \left(\{\mathbf{w}_i^{\text{DL}}\}, \{\mathbf{v}_i^{\text{UL}}\} \right) = \left(\sum_{n=1}^{N} \mathbf{1}_n \left(\{\mathbf{w}_{i,n}^{\text{DL}}\}, \{\mathbf{v}_{i,n}^{\text{UL}}\} \right) P_{c,n} + \sum_{i=1}^{K} \|\mathbf{w}_i^{\text{DL}}\|^2 \right) + \lambda \left(\sum_{i=1}^{K} p_i^{\text{UL}} \right) \tag{9}$$

where $\lambda \geq 0$ is a weight to trade off between the total energy consumptions between active APs and all MUs.

3. PROBLEM FORMULATION

In this paper, we jointly optimize the DL and UL user-AP association and transmit/receive beamforming by considering the following UABF problem.

$$\text{(P1)}: \min_{\{\mathbf{w}_i^{\text{DL}}\}, \{\mathbf{v}_i^{\text{UL}}\}, \{p_i^{\text{UL}}\}} \; P_{\text{total}} \left(\{\mathbf{w}_i^{\text{DL}}\}, \{\mathbf{v}_i^{\text{UL}}\} \right) \tag{10}$$

$$\text{s.t. } \text{SINR}_i^{\text{DL}} \geq \gamma_i^{\text{DL}}, \forall i \in \mathcal{K} \tag{11}$$

$$\text{SINR}_i^{\text{UL}} \geq \gamma_i^{\text{UL}}, \forall i \in \mathcal{K} \tag{12}$$

$$p_i^{\text{UL}} \geq 0, \forall i \in \mathcal{K} \tag{13}$$

where γ_i^{DL} and γ_i^{UL} are the given SINR requirements for MU i for the DL and UL transmissions, respectively.

Problem (P1) can be shown to be non-convex due to the implicit integer programming involved due to indicator function $\mathbf{1}_n(\cdot)$'s in the objective. However, given the fact that the static (non-transmission related) power, i.e., $P_{c,n}$, is in practice significantly larger than the transmit power at each AP n, to minimize the total network energy consumption, it is conceivable that for the optimal solution of (P1) only a small subset of N APs need to be "on". As a result, a "group-sparse" property can be inferred from the following concatenated beamforming vector:

$$\left[[\hat{\mathbf{w}}_1^{\text{DL}}, \hat{\mathbf{v}}_1^{\text{UL}}], \cdots, [\hat{\mathbf{w}}_N^{\text{DL}}, \hat{\mathbf{v}}_N^{\text{UL}}] \right] \tag{14}$$

in which the beamforming vectors are grouped according to their associated APs, i.e., $\hat{\mathbf{w}}_n^{\text{DL}} = \left[(\mathbf{w}_{1,n}^{\text{DL}})^T, \cdots, (\mathbf{w}_{K,n}^{\text{DL}})^T \right]$ and $\hat{\mathbf{v}}_n^{\text{UL}} = \left[(\mathbf{v}_{1,n}^{\text{UL}})^T, \cdots, (\mathbf{v}_{K,n}^{\text{UL}})^T \right]$, $n = 1, \cdots, N$. If AP n is off, its corresponding block $[\hat{\mathbf{w}}_n^{\text{DL}}, \hat{\mathbf{v}}_n^{\text{UL}}]$ in (14) needs to be zero. Consequently, the fact that only a small subset of deployed APs is selected to be on implies that the concatenated beamforming vector in (14) should contain only a very few non-zero block components.

One well-known approach to enforce desired group sparsity in the obtained solutions for optimization problems is by adding to the objective function an appropriate penalty term. The widely used group sparsity enforcing penalty function, which was first introduced in the context of the group least-absolute selection and shrinkage operator (LASSO) problem [18], is the mixed $\ell_{1,2}$ norm. In our case, such a penalty is expressed as

$$\sum_{n=1}^{N}\left\|\left[\hat{\mathbf{w}}_n^{\mathrm{DL}},\hat{\mathbf{v}}_n^{\mathrm{UL}}\right]\right\|. \tag{15}$$

The $\ell_{1,2}$ norm in (15), similar to ℓ_1 norm, offers the closest convex approximation to the ℓ_0 norm over the vector consisting of ℓ_2 norms $\left\{\left\|[\hat{\mathbf{w}}_n^{\mathrm{DL}},\hat{\mathbf{v}}_n^{\mathrm{UL}}]\right\|\right\}_{n=1}^{N}$, implying that each $\left\|[\hat{\mathbf{w}}_n^{\mathrm{DL}},\hat{\mathbf{v}}_n^{\mathrm{UL}}]\right\|$ is desired to be set to zero to obtain group sparsity. Note that the same idea has also been used in [12–15] for the DL user-AP association and beamforming design involving only $\mathbf{w}_i^{\mathrm{DL}}$'s.

Similar to [12–15], at first glance it seems that Problem (P1) can be approximately solved by replacing the objective function with

$$\sum_{n=1}^{N}\beta_n\sqrt{\sum_{i=1}^{K}\|\mathbf{w}_{i,n}^{\mathrm{DL}}\|^2+\|\mathbf{v}_{i,n}^{\mathrm{UL}}\|^2}+\sum_{i=1}^{K}\|\mathbf{w}_i^{\mathrm{DL}}\|^2+\lambda\sum_{i=1}^{K}p_i^{\mathrm{UL}} \tag{16}$$

where $\beta_n \geq 0$ indicates the relative importance of the penalty term associated with AP n, which can be set in proportion to $P_{c,n}$.

However, Problem (P1) with (16) as the objective function is still non-convex due to the constraints in (11) and (12). Furthermore, since the UL receive beamforming vector $\mathbf{v}_i^{\mathrm{UL}}$'s can be scaled down to be arbitrarily small without affecting the UL SINR defined in (6), minimizing (16) directly will result in all $\mathbf{v}_i^{\mathrm{UL}}$'s going to zero. As a result, the $\ell_{1,2}$ norm penalty term in (16) does not work for the AP selection in our problem, and hence the algorithms proposed in [12–15], which involves only the DL transmit beamforming vector $\mathbf{w}_i^{\mathrm{DL}}$'s, cannot be used directly to solve our problem.

4. PROPOSED SOLUTION

In this section, we propose a new algorithm for Problem (P1) which exploits "group-sparse" optimization and yet overcomes the receive beamforming scaling issue mentioned in Section 3. First, we consider the following transmit sum-power minimization problem in the UL:

$$\begin{aligned}\underset{\{\mathbf{v}_i^{\mathrm{UL}}\},\{p_i^{\mathrm{UL}}\}}{\texttt{Min.}}\quad & \sum_{i=1}^{K}p_i^{\mathrm{UL}}\\ \texttt{s.t.}\quad & \mathrm{SINR}_i^{\mathrm{UL}}\geq\gamma_i^{\mathrm{UL}},\forall i\in\mathcal{K}\\ & p_i^{\mathrm{UL}}\geq 0,\forall i\in\mathcal{K}.\end{aligned} \tag{17}$$

From [16], it follows that Problem (17) can be solved in a virtual DL channel as

$$\begin{aligned}\underset{\{\mathbf{w}_i^{\mathrm{VDL}}\}}{\texttt{Min.}}\quad & \sum_{i=1}^{K}\|\mathbf{w}_i^{\mathrm{VDL}}\|^2\\ \texttt{s.t.}\quad & \mathrm{SINR}_i^{\mathrm{VDL}}\triangleq\frac{|\mathbf{h}_i^T\mathbf{w}_i^{\mathrm{VDL}}|^2}{\sum_{j\neq i}|\mathbf{h}_i^T\mathbf{w}_j^{\mathrm{VDL}}|^2+\sigma^2}\geq\gamma_i^{\mathrm{UL}},\forall i\in\mathcal{K}\end{aligned} \tag{18}$$

where $\mathbf{w}_i^{\mathrm{VDL}}\in\mathbb{C}^{M\times 1}$ is the virtual DL transmit beamforming vector over N APs for MU i. Denote $\left(\mathbf{v}_i^{\mathrm{UL}}\right)'$, $\left(p_i^{\mathrm{UL}}\right)'$ and $\left(\mathbf{w}_i^{\mathrm{VDL}}\right)'$ as the optimal solutions to problems (17) and (18), respectively. Then from [16] it follows that $\left(\mathbf{v}_i^{\mathrm{UL}}\right)'$ and $\left(\mathbf{w}_i^{\mathrm{VDL}}\right)'$ can be made identical, $i=1,\cdots,N$, and furthermore $\sum_{i=1}^{K}\left(p_i^{\mathrm{UL}}\right)'=\sum_{i=1}^{K}\|\left(\mathbf{w}_i^{\mathrm{VDL}}\right)'\|^2$.

By establishing a virtual DL transmission for the UL transmission in C-RAN based on the above UL-DL duality result, Problem (P1) can be reformulated as

$$\begin{aligned}(\mathrm{P2}):\quad \underset{\{\mathbf{w}_i^{\mathrm{DL}}\},\{\mathbf{w}_i^{\mathrm{VDL}}\}}{\texttt{Min.}}\quad & \sum_{n=1}^{N}\mathbf{1}_n\left(\{\mathbf{w}_{i,n}^{\mathrm{DL}}\},\{\mathbf{w}_{i,n}^{\mathrm{VDL}}\}\right)P_{c,n}\\ & +\sum_{i=1}^{K}\|\mathbf{w}_i^{\mathrm{DL}}\|^2+\lambda\sum_{i=1}^{K}\|\mathbf{w}_i^{\mathrm{VDL}}\|^2 \qquad (19)\\ \texttt{s.t.}\quad & \mathrm{SINR}_i^{\mathrm{DL}}\geq\gamma_i^{\mathrm{DL}},\forall i\in\mathcal{K} \qquad (20)\\ & \mathrm{SINR}_i^{\mathrm{VDL}}\geq\gamma_i^{\mathrm{UL}},\forall i\in\mathcal{K}. \qquad (21)\end{aligned}$$

The equivalence between problems (P1) and (P2) can be proven by showing that for any given feasible solution to Problem (P2), we can always find a corresponding feasible solution to Problem (P1) similar as [17, Proposition 1]; thus, problems (P1) and (P2) achieve the same optimal value with the same set of optimal DL/UL beamforming vectors.

Since Problem (P2) is merely a DL problem that has the same "group-sparse" property as (P1), it can be approximately solved by replacing the objective function with

$$\sum_{n=1}^{N}\beta_n\sqrt{\sum_{i=1}^{K}\|\mathbf{w}_{i,n}^{\mathrm{DL}}\|^2+\|\mathbf{w}_{i,n}^{\mathrm{VDL}}\|^2}+\sum_{i=1}^{K}\|\mathbf{w}_i^{\mathrm{DL}}\|^2+\lambda\sum_{i=1}^{K}\|\mathbf{w}_i^{\mathrm{VDL}}\|^2. \tag{22}$$

Comparing (22) and (16), we have successfully solved the scaling issue of UL receive beamforming vector, $\mathbf{v}_i^{\mathrm{UL}}$'s, by replacing them with the equivalent DL transmit beamforming vector, $\mathbf{w}_i^{\mathrm{VDL}}$'s, since from (18) it follows that the virtual DL SINR of each MU i is no more scaling invariant to $\mathbf{w}_i^{\mathrm{VDL}}$'s.

Furthermore, since any arbitrary phase rotation of the beamforming vectors does not affect both (22) and the SINR constrains in (20) and (21), (P2) with (22) as the objective function can be reformulated as a convex second-order cone programming (SOCP) [19], which is given by

$$\begin{aligned}(\mathrm{P3}):&\\ \underset{\{\mathbf{w}_i^{\mathrm{DL}}\},\{\mathbf{w}_i^{\mathrm{VDL}}\},\{t_n\}}{\texttt{Min.}}\quad & \sum_{n=1}^{N}\beta_n t_n+\sum_{i=1}^{K}\|\mathbf{w}_i^{\mathrm{DL}}\|^2+\lambda\sum_{i=1}^{K}\|\mathbf{w}_i^{\mathrm{VDL}}\|^2 \qquad (23)\\ \texttt{s.t.}\quad & \left\|\begin{matrix}\mathbf{h}_i^H\mathbf{W}^{\mathrm{DL}}\\ \sigma\end{matrix}\right\|\leq\sqrt{1+\frac{1}{\gamma_i^{\mathrm{DL}}}}\mathbf{h}_i^H\mathbf{w}_i^{\mathrm{DL}},\forall i\in\mathcal{K} \qquad (24)\\ & \left\|\begin{matrix}\mathbf{h}_i^T\mathbf{W}^{\mathrm{VDL}}\\ \sigma\end{matrix}\right\|\leq\sqrt{1+\frac{1}{\gamma_i^{\mathrm{UL}}}}\mathbf{h}_i^T\mathbf{w}_i^{\mathrm{VDL}},\forall i\in\mathcal{K} \qquad (25)\\ & \sqrt{\sum_{i=1}^{K}\|\mathbf{w}_{i,n}^{\mathrm{DL}}\|^2+\|\mathbf{w}_{i,n}^{\mathrm{VDL}}\|^2}\leq t_n,\forall n\in\mathcal{N} \qquad (26)\end{aligned}$$

where $\mathbf{W}^{\mathrm{DL}}=[\mathbf{w}_1^{\mathrm{DL}},\cdots,\mathbf{w}_K^{\mathrm{DL}}]$, $\mathbf{W}^{\mathrm{VDL}}=[\mathbf{w}_1^{\mathrm{VDL}},\cdots,\mathbf{w}_K^{\mathrm{VDL}}]$, and t_n's are auxiliary variables with $t_n=0$ and $t_n>0$ indicating that

AP n is switched off and on, respectively. Notice that without $\ell_{1,2}$ norm penalty or $\beta_n = 0, \forall n \in \mathcal{N}$, Problem (P3) can be decomposed into two separate minimum-power beamforming design problems: one for the original DL transmission, and the other for the virtual DL transmission.

Remark 4.1 *Conventionally, the UL transmit sum-power minimization problem, as in (17), has an analytical structure and thus is computationally easier to handle, as compared to the DL minimum-power beamforming design problem, as in (18). Consequently, most existing studies in the literature have transformed the DL problem to its virtual UL formulation for convenience. The motivation of exploiting the reverse direction in this work, however, is to overcome the scaling issue of UL receive beamforming in "group-sparse" optimization, so that we can apply the $\ell_{1,2}$ norm penalty to solve the AP selection problem in (P2).*

Next, we present the complete algorithm for Problem (P1), in which three steps need to be performed sequentially.

1. *Identify the subset of active APs denoted as $\mathcal{N}_{on}$.* This can be done by iteratively solving Problem (P3) with different β_n's. Notice that how to set the parameter β_n's in (P3) plays a key role in the resulting APs selection. To optimally set the values of β_n's, we adopt an iterative method similar as in [20], shown as follows. In the lth iteration, $l \geq 1$, $t_n^{(l)}$'s are obtained by solving Problem (P3) with $\beta_n = \beta_n^{(l)}, \forall n \in \mathcal{N}$. The $\beta_n^{(l)}$'s are derived from the solution $t_n^{(l-1)}$'s of the $(l-1)$th iteration as

$$\beta_n^{(l)} = \frac{P_{c,n}}{t_n^{(l-1)} + \varepsilon}, n = 1, \cdots, N \quad (27)$$

where ε is a small positive number to ensure stability. Notice that the initial values of $t_n^{(0)}$'s are chosen as

$$t_n^{(0)} = \sqrt{\sum_{i=1}^{K} \|\tilde{\mathbf{w}}_{i,n}^{\mathrm{DL}}\|^2 + \|\tilde{\mathbf{w}}_{i,n}^{\mathrm{VDL}}\|^2}, n = 1, \cdots, N \quad (28)$$

where $\tilde{\mathbf{w}}_{i,n}^{\mathrm{DL}}$ and $\tilde{\mathbf{w}}_{i,n}^{\mathrm{VDL}}$ are the beamforming vector solution of Problem (P3) with $\beta_n = 0, \forall n \in \mathcal{N}$. The above update is repeated until $|\beta_n^{(l)} - \beta_n^{(l-1)}| < \eta, \forall n \in \mathcal{N}$, where η is a small positive constant that controls the algorithm accuracy.

Let $\mathbf{t}^\star = [t_1^\star, \cdots, t_N^\star]$ denote the sparse solution after the convergence of the above iterative algorithm.[1] Then the nonzero entries in $\mathbf{t}^\star$ correspond to the APs that need to be "on", i.e., $\mathcal{N}_{\mathrm{on}} = \{n | t_n^\star > 0, n \in \mathcal{N}\}$.

2. *Obtain the optimal transmit/receive beamforming vectors $\left(\mathbf{w}_i^{DL}\right)^\star$ and $\left(\mathbf{w}_i^{VDL}\right)^\star$, $i = 1, \cdots, K$, given the selected on APs.* This can be done by solving (P3) with $\beta_n = 0, \forall n \in \mathcal{N}$ and $\mathbf{w}_{i,n}^{\mathrm{DL}} = \mathbf{w}_{i,n}^{\mathrm{VDL}} = \mathbf{0}, i = 1, ..., K, \forall n \notin \mathcal{N}_{\mathrm{on}}$.

3. *Obtain the optimal transmit power values of MUs $\left(p_i^{UL}\right)^\star$, $i = 1, \cdots, K$.* This can be done by solving Problem (17) with $\mathbf{v}_i^{\mathrm{UL}} = \left(\mathbf{w}_i^{\mathrm{VDL}}\right)^\star$, $\forall i \in \mathcal{K}$, which is a simple linear programming (LP) problem.

[1]The iterative update given in (27) is designed to make small entries in $\{t_n\}_{n=1}^N$ converge to zero. Convergence of this algorithm can be shown by identifying the iterative update as a Majorization-Minimization (MM) algorithm [21] for a concave minimization problem, the details of which are omitted due to the space limitation.

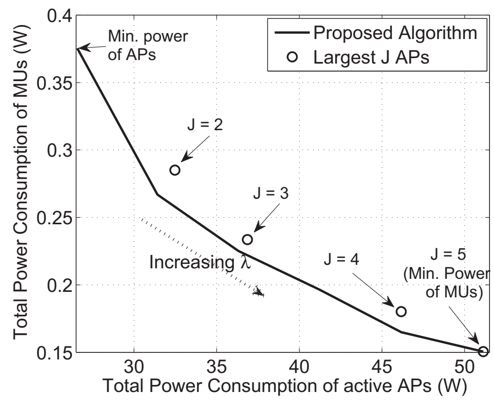

Fig. 1. Sum-power consumption tradeoffs between active APs and MUs.

5. NUMERICAL RESULTS

In this section, we present numerical results to verify our proposed algorithm. We consider a C-RAN consisting of $N = 10$ APs serving $K = 4$ MUs, where all the APs and MUs are uniformly distributed in a square area with size of 1 Km. The SINR requirements are set to be $\gamma_i^{\mathrm{DL}} = 12$dB and $\gamma_i^{\mathrm{UL}} = 10$dB, $\forall i \in \mathcal{K}$, which may correspond to the application of highly interactive gaming or video conferencing by wireless users. For each AP, we set the static power as $P_{c,n} = 5$W and assume single antenna, i.e., $M_n = 1, \forall n \in \mathcal{N}$. We assume a simplified channel model with the distance-dependent attenuation with pathloss exponent $\alpha = 3$ and an additional random term (exponentially distributed with unit mean) accounting for short-term Rayleigh fading. We also set the receiver noise power for all the APs and MUs as $\sigma^2 = -50$dB.

Fig.1 shows the sum-power consumption tradeoffs between active APs and all MUs achieved by the proposed algorithm with different values of λ. For comparison, we also simulate one heuristic algorithm termed **Largest J APs (LJA)**. In the LJA algorithm, each MU i is associated with J APs corresponding to the first J best channels of largest $\|\mathbf{h}_{i,n}\|$, $n = 1, \cdots, N$, with $1 \leq J \leq N$. Then with the selected "on" APs for all MUs, the optimal DL and UL beamforming and power minimization problems are separately solved (c.f. (P3) with $\beta_n = 0$, $\forall n \in \mathcal{N}$). Notice that the case of $J = 1$ is not shown in Fig. 1 since in this case (P1) is infeasible. It is observed that for our proposed algorithm, as λ increases, the total power consumption of active APs increases and that of all MUs decreases. For the LJA algorithm, similar power tradeoffs are observed as J increases. The power saving by the the proposed algorithm over the LJA algorithm is also observed thanks to the joint user-AP association and beamforming design in the proposed algorithm.

6. CONCLUSION

In this paper, we consider the C-RAN with densely deployed APs cooperatively serving distributed MUs for both the UL and DL transmissions. We study the problem of joint DL and UL user-AP association and beamforming (UABF) design to minimize the energy consumption tradeoffs between the active APs and MUs by exploiting "group-sparse" optimization. To tackle the UL receive beamforming scaling issue in "group-sparse" optimization, a virtual DL transmission is established based on the UL-DL duality, and thereby an efficient solution for the UABF problem is obtained.

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