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Joint resource optimization for energy efficient full-duplex heterogeneous C-RAN system

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Abstract

In this paper, we study a joint resource allocation algorithm for energy efficiency (EE) of a cloud radio access network (C-RAN) with full-duplex (FD) remote radio heads (RRHs), which enable simultaneous uplink and downlink communications. To solve the joint optimization problem, we utilize a successive convex approximation (SCA) based joint antenna selection and power allocation (JASPA) algorithm. In addition, we present an improved multi-candidate remote radio heads (RRHs) user association (MCRUA) algorithm. The simulation results show that the proposed joint resource allocation algorithm has a fast convergence speed and a significant gain in the EE for FD C-RAN.

INTRODUCTION

Cloud radio access network (C-RAN) has been considered by both the operators and the equipment vendors for fifth-generation (5G) mobile networks to reduce both capital and operating expenditures [1], [2]. C-RAN has been shown to provide high spectral efficiency and energy efficiency (EE). In C-RAN, the baseband unit (BBU) is located in the center of a cell, and is connected to remote radio heads (RRHs) through optical transmission network. The BBU acts as a digital unit implementing the base station functionality from baseband processing to packet processing. The RRHs perform radio functions which include frequency conversion, amplification, and A/D and D/A conversion. The RRHs send/receive digitalized signals to/from the BBU pool via optical fiber, and antennas are equipped with RRHs to transmit/ receive radio frequency (RF) signals. The basic idea of the C-RAN is that the transmission distance between antennas and mobile users (MUs) is reduced, so that significant improvement to the EE are achieved. From the viewpoint of green information technology, the EE has recently attracted more attention. Thus, the resource allocation for EE maximization has attracted considerable attention. However, most existing works on resource allocation for the EE of C-RAN have been considered as the separated optimization problems operating on the traditional half duplex (HD) communication systems [3], [4].

Nowadays FD radios have emerged as an attractive solution to increase the throughput of wireless communication systems [5], [6]. FD transmission allows downlink and uplink transmission to occur simultaneously at the same frequency. FD radios have the potential to double the spectral efficiency of conventional HD communication systems.

In this paper, we study a resource allocation algorithm to maximize the downlink EE in FD C-RAN by solving a joint optimization problem. To solve the complex joint optimization problem, we utilize a successive convex approximation (SCA) based joint antenna selection and power allocation (JASPA) algorithm [7]. Furthermore, we present an improved multi-candidate RRHs user association (MCRUA) algorithm. This algorithm utilizes the tabu search technique [8], [9] to obtain the appropriate large-scale fading threshold (LSFT) for EE improvement. Finally, we present a joint resource allocation algorithm with fast convergence which is based on the Dinkelbach method [10] for solving nonlinear fractional problems.

SYSTEM MODEL

A C-RAN system with L hexagonal cells is considered. In each cell there are N FD RRHs and K MUs are uniformly distributed. The K MUs use single antenna HD mobile communication devices to have low hardware complexity. $K_{U,j}$ and $K_{D,j}$ users in the j-th cell are scheduled for simultaneous uplink and downlink transmissions, respectively, such that $K_{U,j}+K_{D,j}=K$. We also assume that the n-th RRH in the j-th cell is equipped with M_{jn} antennas and the total number of system antennas in the j-th cell is given by $\sum_{n=1}^{N} M_{jn}=M_{\max}$. The channel vector between the RRHs in the l-th cell and the k-th MU in the j-th cell is denoted as $\mathbf{g}_{jkl}=\mathbf{\Lambda}_{jkl}^{1/2}\mathbf{h}_{jkl}$ where $\mathbf{\Lambda}_{jkl}=\mathrm{diag}\left([\lambda_{jkl1},\cdots,\lambda_{jklN}]^{\mathrm{T}}\right)\otimes\mathbf{I}_N$, $\lambda_{jkln}\triangleq ad_{jkln}^{-\alpha}$, and $\mathbf{h}_{jkl}=[\mathbf{h}_{jkl1}^{\mathrm{T}},\ldots,\mathbf{h}_{jklN}^{\mathrm{T}}]^{\mathrm{T}}$. Here, λ_{jkln} represents the long-term path loss between the k-th MU in the j-th cell and the n-th RRH in the l-th cell. d_{jkln} represents the distance between the k-th MU in the j-th cell and the n-th RRH in the l-th cell. $\otimes$ represents the Kronecker product, a is the path loss gain, and α is the path loss exponent. $\mathbf{h}_{jkln}$ denotes an $M_{ln}\times 1$ small-scale fading channel vector which contains independent and identically distributed circularly symmetric complex Gaussian random variables with zero mean and unit variance.

The minimum mean-square error channel estimation for the channel vector is given by $\hat{\mathbf{g}}_{jkl} = \mathbf{\Lambda}_{jkl}\mathbf{Q}_{jk}^{-1}\mathbf{y}_{\mathrm{P},jk}$ where $\mathbf{Q}_{jk}^{-1} = \left(\sum_{l=1}^{L}\mathbf{\Lambda}_{jkl} + \sigma_{\mathrm{P}}^2\mathbf{I}_{M_{\max}}\right)$ and $\mathbf{y}_{\mathrm{P},jk} = \sum_{l=1}^{L}\mathbf{g}_{jkl} + \mathbf{z}_{lk}$ is $M_{\max}\times 1$ received pilot signal. Here, the large-scale fading between the n-th RRH in the l-th cell and the k-th MU in the j-th cell is given by $\beta_{jkln} = \lambda_{jkln}\left(\sum_{l=1}^{L}\lambda_{jkln} + \sigma_{\mathrm{P}}^2\right)^{-1/2}$. The receiver′s additive white Gaussian noise vector $\mathbf{z}_{lk}$ is $\mathcal{CN}(0,\sigma_{\mathrm{P}}^2\mathbf{I}_{M_{\max}})$. The channel vector $\mathbf{g}_{jkl}$ can be decomposed as $\mathbf{g}_{jkl} = \hat{\mathbf{g}}_{jkl} + \tilde{\mathbf{g}}_{jkl}$ where $\tilde{\mathbf{g}}_{jkl} \sim CN(0,\mathbf{\Lambda}_{jkl} - \mathbf{\Lambda}_{jkl}\mathbf{Q}_{jk}^{-1}\mathbf{\Lambda}_{jkl})$.

The maximum ratio transmission beamforming is used and the user association matrix $\mathbf{A}_j$ in the j-th cell is denoted as

$$a_{jkn} = \begin{cases} 1, \text{ if } \mathbf{w}_{jkn} = \hat{\mathbf{g}}_{jkn} \ (n\text{-th RRH is associated with } k\text{-th user}) \\ 0, \text{ if } \mathbf{w}_{jkn} = \mathbf{0} \ (n\text{-th RRH is not associated with } k\text{-th user}) \end{cases}$$

(1)

The downlink transmitted signal from all RRHs in the j-th cell is expressed as $\mathbf{x}_j = \sum_{k=1}^{K_{D,j}}\mathbf{w}_{jk}x_{jk}$ where $\mathbf{w}_{jk} = [\mathbf{w}_{jk1}^{\mathrm{T}},\cdots,\mathbf{w}_{jkN}^{\mathrm{T}}]^{\mathrm{T}}$ is the beamforming vector used to send the data symbol x_{jk} to k-th MU. The received signal at the k-th MU in the j-th cell is given by

$$y_{jk} = \sum_{l=1}^{L}\sqrt{p_{jk}}\mathbf{g}_{jkl}^{\mathrm{H}}\mathbf{x}_l + \sum_{l=1}^{L}\sum_{i=1}^{K_{U,l}}q_{jkli}s_{li} + z_{jk} \qquad (2)$$

where z_{jk} is the receiver noise at the k-th MU in the j-th cell given by $z_{jk} \sim \mathcal{CN}(0,\sigma^2)$. $s_{li} = \sqrt{\hat{p}_{li}}d_{li}$ is the transmitted signal of the uplink user *i* in the *l*-th cell, $\hat{p}_{li}$ is the transmit power sent from uplink user *i* in the *l*-th cell, d_{li} is the transmit data symbol sent from uplink user *i* in the *l*-th cell, q_{jkli} is the channel coefficient between the downlink user *k* in the *j*-th cell and the uplink user *i* in the *l*-th cell. Thus, the downlink signal-to-interference-plus-noise ratio (SINR) of the k-th MU in the j-th cell is given by

$$\gamma_{jk}(\mathbf{A}_j,\mathbf{m}_j,\mathbf{p}_j) = \frac{\left|\mathbb{E}\left[\sqrt{p_{jk}}\mathbf{g}_{jkj}^{H}\hat{\mathbf{g}}_{jkj}\right]\right|^2}{I+\sigma^2}. \qquad (3)$$

Here $I = \mathrm{var}\left[\sqrt{p_{jk}}\mathbf{g}_{jkj}^{H}\hat{\mathbf{g}}_{jkj}\right] + \sum_{(l,i)\neq(j,k)}\left|\mathbb{E}\left[\sqrt{p_{li}}\mathbf{g}_{jkl}^{H}\hat{\mathbf{g}}_{lil}\right]\right|^2$

$$+\sum_{l=1}^{L}\sum_{i=1}^{K_{U,i}}\hat{p}_{li}\left|q_{jkli}\right|^2. \qquad (4)$$

$\mathbf{p}_j = [p_{j1},p_{j2},\ldots,p_{jK}]^T$ is the transmit power from the RRHs to each MU in the j-th cell, and $\mathbf{m}_j = [m_{j1},m_{j2},\ldots,m_{jN}]^T$ denotes the number of active antennas at each RRH in the j-th cell.

The achievable rate in the downlink of the k-th MU in the j-th cell is given by

$$C_{jk}(\mathbf{A}_j,\mathbf{m}_j,\mathbf{p}_j) = B\log_2\left(1+\gamma_{jk}(\mathbf{A}_j,\mathbf{m}_j,\mathbf{p}_j)\right) \qquad (5)$$

where B is the bandwidth. Then, we describe the total network power consumption in the j-th cell as follows

$$P_j\left(\mathbf{A}_j,\mathbf{m}_j,\mathbf{p}_j\right) = p_c\sum_{n=1}^{N}m_{jn} + \sum_{n=1}^{N}\sum_{k=1}^{K}p_{jk}a_{jkn} + p_0 \qquad (6)$$

where p_c is the circuit power consumption per antenna, which is independent of the transmit power. p_0 is the static power consumption at the RRH and BBU. Thus, the system EE is given by

$$\eta_j\left(\mathbf{A}_j,\mathbf{m}_j,\mathbf{p}_j\right) = \frac{\sum_{k=1}^{K}C_{jk}\left(\mathbf{A}_j,\mathbf{m}_j,\mathbf{p}_j\right)}{P_j\left(\mathbf{A}_j,\mathbf{m}_j,\mathbf{p}_j\right)} \qquad (7)$$

PROBLEM FORMULATION

The system objective is to maximize the system EE taking into account the downlink transmit powers and QoS for reliable transmission. The joint optimized resource allocation algorithm is given by solving the following optimization problem:

$$\underset{\mathbf{A}_j,\mathbf{m}_j,\mathbf{p}_j}{\text{maximize}}\ \eta_j(\mathbf{A}_j,\mathbf{m}_j,\mathbf{p}_j) \qquad (8)$$

$$\text{s.t } C_{jk} \geq C_{\min}, \forall k \qquad (9)$$

$$\sum_{k=1}^{K}p_{jk} \leq P_{\max} \qquad (10)$$

$$1 \leq \sum_{n=1}^{N}a_{jkn} \leq N, \forall k \qquad (11)$$

$$0 \leq m_{jn} \leq M_{\max}/N, \forall n \qquad (12)$$

(9) implies the minimum data rate requirements and (10) represents the constraints for downlink transmit powers. (11) is the constraint for the minimum number of MU association and (12) represents the constraint for the number of active antennas.

Joint Resource Allocation Algorithm

In this section, the joint resource allocation algorithm is described to maximize the system EE. This main algorithm consists of two sub-algorithms called as Algorithm 1 and 2. Algorithm 1 is for the optimization of JASPA and Algorithm 2 is for the optimization of user association.

In Algorithm 1, we fix $\mathbf{A}_j$ and solve problem (8) to obtain $\mathbf{m}_j$ and $\mathbf{p}_j$ by using the SCA technique to approximate the objective function based on the following equation:

$$\log(1+\omega_{jk}) \geq f(\omega_{jk},a_{jk},b_{jk}) = a_{jk}\omega_{jk} + b_{jk} \qquad (13)$$

Here a_{jk} and b_{jk} are adaptively calculated variables given by

$$a_{jk}=\frac{\omega_{jk}}{1+\omega_{jk}};\ \ b_{jk}=\log(1+\omega_{jk})-\frac{\omega_{jk}\log\omega_{jk}}{1+\omega_{jk}} \qquad (14)$$

Because of the above convexity approximation, we apply this lower bound approximation $\hat{C}_{jk}=\log(1+r_{jk})$ where ω_{jk} corresponds to r_{jk}. We also replace the variables $\hat{\mathbf{m}}_j=\log\mathbf{m}_j$ and $\hat{\mathbf{p}}_j=\log\mathbf{p}_j$ to employ the approximated optimization problem. Applying $\hat{C}_{jk}(\hat{\mathbf{m}}_j,\hat{\mathbf{p}}_j,a_{jk},b_{jk})=f(\gamma_{jk}(\hat{\mathbf{m}}_j,\hat{\mathbf{p}}_j),a_{jk},b_{jk})$ and $\hat{P}_j(\hat{\mathbf{m}}_j,\hat{\mathbf{p}}_j)$ in (8), the approximated optimization problem of (8) becomes a convex problem due to the concave objective function. Table 1 shows the SCA-based JASPA algorithm.

Table 1. SCA-based JASPA Algorithm.

```
Initially set $\mathbf{a}^{(0)}=1,\mathbf{b}^{(0)}=0$, and $t=1$
repeat
    Solve the approximation problem of (8) to obtain $\mathbf{m}_j^{(t)},\mathbf{p}_j^{(t)}$
    Compute $\gamma_{jk}(\mathbf{A}_j,\mathbf{m}_j^{(t)},\mathbf{p}_j^{(t)})$ and update $\mathbf{a}^{(t)},\mathbf{b}^{(t)}$ from (14)
    $t=t+1$
until Convergence of $(\mathbf{m}_j^{(t)},\mathbf{p}_j^{(t)})$
return $(\mathbf{m}_j^{\mathrm{Opt}},\mathbf{p}_j^{\mathrm{Opt}})=(\mathbf{m}_j^{(t)},\mathbf{p}_j^{(t)})$
```

For given $\mathbf{m}_j$ and $\mathbf{p}_j$, Algorithm 2 finds an optimal $\mathbf{A}_j$. In this algorithm, the k-th MU is associated with the n-th RRH when large-scale fading between k-th MU and n-th RRH is larger than an LSFT. The MCRUA algorithm is improved to search an optimal LSFT by applying a tabu search. First, the LSFT range is divided into S sections, and this algorithm searches for the local optimal value in each section. Then, the optimum value by using these local optimal values is obtained. This algorithm also iteratively searches the minimum active RRHs until the system EE is converged. The RRH that serves the minimal number of MUs is called as the inefficient RRH. In algorithm 2, the inefficient RRH is iteratively switched into sleep mode. Thus, the improved MCRUA has a more efficient algorithm than the conventional MCRUA which uses the predefined LSFT. Table 2 describes the improved MCRUA algorithm.

Table 2. Improved MCRUA Algorithm.

```
Initially set feasible LSFT $\xi_{jn}^{(s)}$ and $t=1$
repeat
    for $n=1,2,\ldots,N$
        for $s=1,2,\ldots,S$
            while Convergence of $\eta_j^{(s)}(\mathbf{A}_j^{(s)},\mathbf{m}_j,\mathbf{p}_j)$
                $a_{jkn}=1$ if $\beta_{jkln}\ge\xi_{jn}^{(s)}$ and compute $\eta_j^{(s)}(\mathbf{A}_j^{(s)},\mathbf{m}_j,\mathbf{p}_j)$
                Search for optimal $\xi_{jn}^{(s)}$ to maximize $\eta_j^{(s)}(\mathbf{A}_j^{(s)},\mathbf{m}_j,\mathbf{p}_j)$
            end while
        end for
        $\bar{s}=\arg\max_{s}\eta_j^{(s)}(\mathbf{A}_j^{(s)},\mathbf{m}_j,\mathbf{p}_j)$ and $\mathbf{A}_j^{\mathrm{Opt}}=\mathbf{A}_j^{(\bar{s})}$
    end for
    Compute $\eta_{jk}^{(t)}(\mathbf{A}_j^{(t)},\mathbf{m}_j,\mathbf{p}_j)$ and update $\mathbf{A}_j^{(t)}=\mathbf{A}_j^{\mathrm{Opt}}$
    Search for the inefficient $\tilde{n}$-th RRH and $a_{jk\tilde{n}}=0,\forall k$
    $t=t+1$
until Convergence of $\mathbf{A}_j^{(t)}$
return $\mathbf{A}_j^{Opt}=\mathbf{A}_j^{(t)}$
```

Applying Algorithm 1 and 2, the joint resource allocation algorithm based on the Dinkelbach method is formulated. The joint resource allocation algorithm iteratively optimizes $\mathbf{A}_j$, $\mathbf{m}_j$, and $\mathbf{p}_j$ until the total EE performance is converged.

Table 3. Joint Resource Allocation Algorithm.

```
Initially set $t=1$
repeat
    Use Algorithm 1 to obtain $(\mathbf{m}_j^{\mathrm{Opt}},\mathbf{p}_j^{\mathrm{Opt}})$
    Update $(\mathbf{m}_j^{(t)},\mathbf{p}_j^{(t)})=(\mathbf{m}_j^{\mathrm{Opt}},\mathbf{p}_j^{\mathrm{Opt}})$
    Use Algorithm 2 to obtain $\mathbf{A}_j^{\mathrm{Opt}}$
    Update $\mathbf{A}_j^{(t)}=\mathbf{A}_j^{\mathrm{Opt}}$
until Convergence of $\eta_j(\mathbf{A}_j^{(t)},\mathbf{m}_j^{(t)},\mathbf{p}_j^{(t)})$
return $\eta_j(\mathbf{A}_j^{\mathrm{Opt}},\mathbf{m}_j^{\mathrm{Opt}},\mathbf{p}_j^{\mathrm{Opt}})=\eta_j(\mathbf{A}_j^{(t)},\mathbf{m}_j^{(t)},\mathbf{p}_j^{(t)})$
```

SIMULATION RESULTS

It is assumed that the C-RAN system is composed of $L=7$ hexagonal cells. Each cell has $N=7$ RRHs and $K=15$ MUs. In each cell, the total number of system antennas is $M_{\max}=140$. We set the power parameter $P_{\max}=1\text{mW}$, $p_c=1\text{W}$, and $p_0=10\text{W}$. The noise parameter σ^2 and σ_{P}^2 are all -120 dBm and the path-loss exponent α is 4.

Fig. 1 compares the system EE of various user association schemes. Full association implies that all MU are associated with all RRHs in each cell. Nearest RRH and MCRUA are the user association schemes which are referred in [11]. The simulation result shows that the proposed improved MCRUA algorithm achieves a higher EE performance than the other user association schemes.

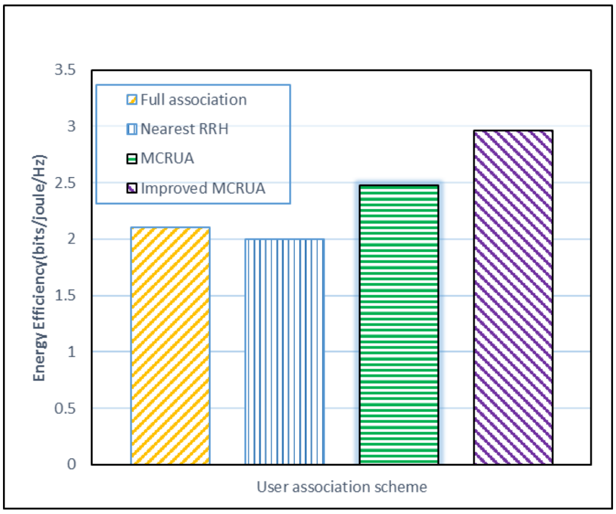

Figure 1. Energy efficiency versus user association schemes.

Fig. 2 shows the system EE versus the iteration number. The proposed joint resource allocation is compared with the improved MCRUA for various active antennas and transmit power constraints. Algorithm 3 denotes the proposed joint resource allocation algorithm. One can see that the proposed joint resource allocation algorithm has a fast convergence speed and achieves a higher EE than the algorithm 2.

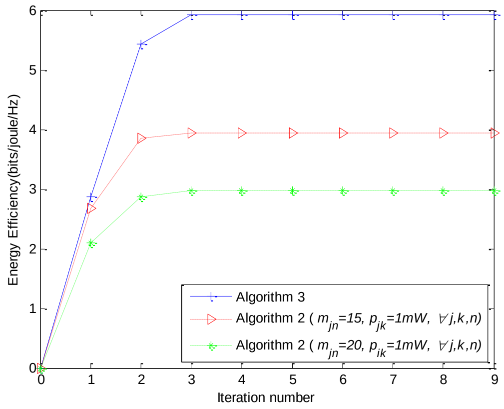

Figure 2. Energy efficiency versus iteration number.

CONCLUSION

In this paper, we proposed an energy efficient joint resource allocation algorithm for FD C-RAN. To solve the joint resource allocation, we employed an SCA-based JASPA and proposed an improved MCRUA. The simulation result shows that it is possible to achieve a significant gain in the EE of the proposed joint resource allocation algorithm for FD C-RAN. Also the proposed algorithm has a fast convergence speed.

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