Compressed Cooperative Reception for the Uplink of C-RAN With Wireless Fronthaul

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***Abstract*—This work deals with a joint design of radio access and fronthaul links for the uplink of cloud radio access network (C-RAN) equipped with wireless fronthaul link. A conventional uplink system based on per-cell decode-and-forward (DF) relaying, in which the message sent by each user equipment (UE) is decoded by the closest remote radio head (RRH) and forwarded to a baseband processing unit (BBU) via wireless fronthaul link, is first reviewed. Since decoding at each RRH might be affected by the interference signals of the other UEs, we present a compress-and-forward (CF) based cooperative reception scheme whereby each RRH quantizes and compresses its received signal and transmits the quantization output to the BBU through the fronthaul link. For the both approaches based on the DF and CF relaying, we tackle the problem of maximizing the sum-rate of the UEs subject to the per-UE and per-RRH power constraints. Link-level simulation results are reported that validate the advantages of the CF-based cooperative scheme compared to the DF-based per-cell reception scheme.**

***Index Terms*—C-RAN, wireless fronthaul, compress-and-forward, decode-and-forward.**

I. Introduction

Cloud radio access network (C-RAN) is known to reduce capital and operating expenditures and to provide high spectral efficiency by means of interference management capabilities [1][2]. However, it has been also reported that the fronthaul links connecting a baseband processing unit (BBU) to distributed remote radio heads (RRHs) may be a bottleneck of the system due to high bit rate requirement [3]. In this work, we consider a practical scenario with wireless, rather than costly wired, fronthaul links motivated by rapidly increasing interest on cost-effective wireless fronthaul networks [4]-[6]. In a preliminary work [7], the authors tackled the problem of jointly optimizing the wireless fronthaul and access links for the downlink of a C-RAN system. However, despite of its importance, relatively little works have focused on the uplink of C-RAN systems with wireless fronthaul links.

In this work, we study the uplink of a C-RAN where a set of user equipments (UEs) send independent messages to a BBU through a set of RRHs that are connected to the BBU by means of wireless fronthaul links. We first review a conventional *per-cell reception* scheme where each RRH operates as a decode-and-forward (DF) relay. In this approach, the message of each UE is decoded at the closest RRH and then sent to the BBU on the fronthaul link. However, this scheme may show significantly degraded performance due to the impact of the inter-UE interference signals especially at high signal-to-noise ratio (SNR) and when the cluster size is large.

For more efficient interference management, we can instead adopt a *compressed cooperative reception* across the RRHs as in standard C-RAN systems [1][3]. In this system, instead of performing local decoding, the RRHs operate as soft, or compress-and-forward (CF), relays, which means that each RRH quantizes and compresses its received baseband signal and then transmits the output signal to the BBU via the wireless fronthaul link. Based on the quantized signals collected from the RRHs in the cluster, the BBU performs decoding of the messages sent by all the UEs in a centralized manner. For the two approaches discussed above, we formulate the problem of maximizing the sum-rate of the UEs while satisfying the per-UE and per-RRH transmit power constraints. We derive iterative algorithms based on the concave convex procedure (CCCP) approach, and report link-level simulation results that show the advantages of the CF-based cooperative scheme compared to the DF-based per-cell reception strategy.

II. System Model

In the uplink of a C-RAN, N_U UEs transmit independent messages to a BBU through N_R RRHs as illustrated in Fig. 1. The RRHs communicate with the BBU by means of wireless fronthaul links. The numbers of antennas of UE k ($k \in \mathcal{N}_U$), RRH i ($i \in \mathcal{N}_R$) and the BBU are denoted by $n_{U,k}$, $n_{R,i}$ and n_B, respectively, and we define the total number of RRH antennas as $n_R \triangleq \sum_{i\in\mathcal{N}_R} n_{R,i}$. Here $\mathcal{N}_R \triangleq \{1,\ldots,N_R\}$ and $\mathcal{N}_U \triangleq \{1,\ldots,N_U\}$ denote the sets of RRHs and UEs, respectively.

The message M_k sent by UE k is uniformly chosen from a codebook $\{1,\ldots,2^{nR_k}\}$, where n stands for a coding block length assumed to be sufficiently large and R_k equals the rate of the message M_k. We assume that the access and fronthaul links are separated in the frequency or time domain.

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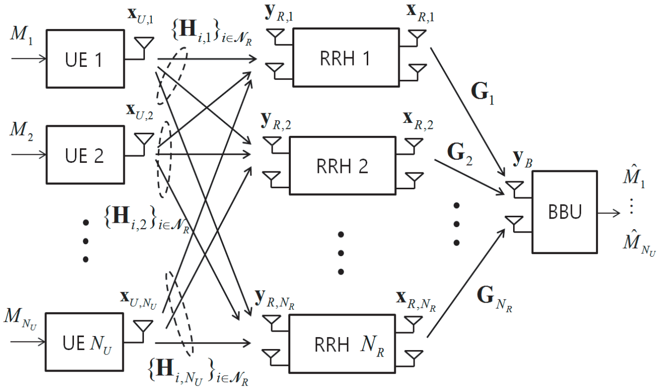

Figure 1. Illustration of the uplink of a C-RAN system with N_U UEs, N_R RRHs and a single BBU.

In the uplink access channel, the signal $\mathbf{y}_{R,i} \in \mathbb{C}^{n_{R,i}\times 1}$ received by RRH i is given as

$$\mathbf{y}_{R,i} = \sum_{k\in\mathcal{N}_U} \mathbf{H}_{i,k}\mathbf{x}_{U,k} + \mathbf{z}_{R,i}, \tag{1}$$

where $\mathbf{x}_{U,k} \in \mathbb{C}^{n_{U,k}\times 1}$ is the signal transmitted by UE k; $\mathbf{H}_{i,k} \in \mathbb{C}^{n_{R,i}\times n_{U,k}}$ represents the channel matrix from UE k to RRH i; and $\mathbf{z}_{R,i} \sim \mathcal{CN}(\mathbf{0},\mathbf{I})$ indicates the additive noise at RRH i. We impose transmission power constraint at each UE k as $\mathbb{E}||\mathbf{x}_{U,k}||^2 \leq P_{U,k}$.

Each RRH i processes the received signal $\mathbf{y}_{R,i}$ to produce the signal $\mathbf{x}_{R,i} \in \mathbb{C}^{n_{R,i}\times 1}$ which is transmitted on the fronthaul link. The signal $\mathbf{y}_B \in \mathbb{C}^{n_B\times 1}$ received by the BBU can be written as

$$\mathbf{y}_B = \sum_{i\in\mathcal{N}_R} \mathbf{G}_i\mathbf{x}_{R,i} + \mathbf{z}_B, \tag{2}$$

where $\mathbf{G}_i \in \mathbb{C}^{n_B\times n_{R,i}}$ defines the channel matrix from RRH i to the BBU, and $\mathbf{z}_B \sim \mathcal{CN}(\mathbf{0},\mathbf{I})$ represents the additive noise at the BBU antennas. We consider per-RRH transmit power constraints as $\mathbb{E}||\mathbf{x}_{R,i}||^2 \leq P_{R,i}$ for $i \in \mathcal{N}_R$. Throughout the paper, we assume that the channel matrices $\{\mathbf{H}_{i,k}\}_{i\in\mathcal{N}_R,k\in\mathcal{N}_U}$ and $\{\mathbf{G}_i\}_{i\in\mathcal{N}_R}$ are estimated and reported to the BBU.

III. DF-Based Per-Cell Reception

This section considers the uplink of conventional cellular systems based on per-cell reception strategy in which the RRHs operate as DF relays. This means that each RRH i decodes the messages sent by a subset $\mathcal{N}_{U,i} \subseteq \mathcal{N}_U$ of UEs from its received signal $\mathbf{y}_{R,i}$ and then encodes the decoded messages to communicate the signal $\mathbf{x}_{R,i}$ with the BBU. Here we define the set $\mathcal{N}_{U,i}$ of UEs that are associated with RRH i such that the messages $\{M_k\}_{k\in\mathcal{N}_{U,i}}$ are decoded by only RRH i. We assume that there is no overlap among the sets $\mathcal{N}_{U,1},\ldots,\mathcal{N}_{U,N_R}$ so that each message M_k is decoded by a single RRH i with $k \in \mathcal{N}_{U,i}$. Since finding the optimal partition $\mathcal{N}_{U,1},\ldots,\mathcal{N}_{U,N_R}$ requires exponential complexity of the number N_U of UEs, we consider a simple policy [8] requiring a linear complexity of N_U, in which each UE is assigned to the closest RRH.

A. RAN Beamforming and Decoding

In the first phase, each UE k encodes its message M_k to produce an encoded baseband signal $\mathbf{s}_k \in \mathbb{C}^{d_k\times 1} \sim \mathcal{CN}(\mathbf{0},\mathbf{I})$ and applies a linear beamforming to the encoded signal as

$$\mathbf{x}_{U,k} = \mathbf{U}_k\mathbf{s}_k, \tag{3}$$

with the beamforming matrix $\mathbf{U}_k \in \mathbb{C}^{n_{U,k}\times d_k}$.

Under the assumption that RRH i decodes the message M_k, $k \in \mathcal{N}_{U,i}$, based on the received signal $\mathbf{y}_{R,i}$, the rates $\{R_k\}_{k\in\mathcal{N}_{U,i}}$ are constrained as

$$\begin{aligned}\sum_{k\in\mathcal{N}_{U,i}} R_k &\leq f_{R,i}(\mathbf{U}) \triangleq I\left(\{\mathbf{s}_k\}_{k\in\mathcal{N}_{U,i}};\mathbf{y}_{R,i}\right) \\ &= \Phi\left(\sum_{k\in\mathcal{N}_{U,i}} \mathcal{T}(\mathbf{H}_{i,k}\mathbf{U}_k),\ \sum_{k\in\mathcal{N}_U\setminus\mathcal{N}_{U,i}} \mathcal{T}(\mathbf{H}_{i,k}\mathbf{U}_k)+\mathbf{I}\right),\end{aligned} \tag{4}$$

with the notation $\mathbf{U} \triangleq \{\mathbf{U}_k\}_{k\in\mathcal{N}_U}$. In (4), we define the functions $\mathcal{T}(\mathbf{X}) \triangleq \mathbf{X}\mathbf{X}^\dagger$ and $\Phi(\mathbf{X},\mathbf{Y}) \triangleq \log_2\det(\mathbf{X}+\mathbf{Y}) - \log_2\det(\mathbf{Y})$, and $I(X,Y)$ represents the mutual information between random variables X and Y.

B. Fronthaul Beamforming and Decoding

After decoding the messages $\{M_k\}_{k\in\mathcal{N}_{U,i}}$, RRH i forms a message $\bar{M}_i$ of rate $\sum_{k\in\mathcal{N}_{U,i}} R_k$ by concatenating the decoded messages $\{M_k\}_{k\in\mathcal{N}_{U,i}}$. Then, it encodes the concatenated message $\bar{M}_i$ to obtain an encoded signal $\mathbf{d}_i \in \mathbb{C}^{d_{f,i}\times 1} \sim \mathcal{CN}(\mathbf{0},\mathbf{I})$ and performs a linear beamforming as

$$\mathbf{x}_{R,i} = \mathbf{V}_i\mathbf{d}_i, \tag{5}$$

with the beamforming matrix $\mathbf{V}_i \in \mathbb{C}^{n_{R,i}\times d_{f,i}}$.

In order to guarantee reasonable scalability with respect to the system size such as the numbers N_R and N_U, we focus on the parallel decoding of the messages $\bar{M}_1,\ldots,\bar{M}_{N_R}$ from the received signal $\mathbf{y}_B$ at the BBU without successive interference cancellation (SIC) (see, e.g., [9]). Then, the rates $\mathbf{R} \triangleq \{R_k\}_{k\in\mathcal{N}_U}$ should satisfy the following constraints:

$$\begin{aligned}\sum_{k\in\mathcal{N}_{U,i}} R_k &\leq f_{B,i}(\mathbf{V}) \triangleq I(\mathbf{d}_i;\mathbf{y}_B) \\ &= \Phi\left(\mathcal{T}(\mathbf{G}_i\mathbf{V}_i),\ \sum_{j\in\mathcal{N}_R\setminus\{i\}} \mathcal{T}(\mathbf{G}_j\mathbf{V}_j)+\mathbf{I}\right),\end{aligned} \tag{6}$$

for all $i \in \mathcal{N}_R$, where we define the notation $\mathbf{V} \triangleq \{\mathbf{V}_i\}_{i\in\mathcal{N}_R}$.

C. Problem Definition and Optimization

Our goal in this work is to maximize the sum-rate $\sum_{k\in\mathcal{N}_U} R_k$ while satisfying the per-UE and per-RRH power constraints. We can formulate the problem as

$$\underset{\mathbf{U},\mathbf{V},\mathbf{R}}{\text{maximize}} \sum_{k\in\mathcal{N}_U} R_k \tag{7a}$$

$$\text{s.t.} \sum_{k\in\mathcal{N}_{U,i}} R_k \leq f_{R,i}(\mathbf{U}),\ i\in\mathcal{N}_R, \tag{7b}$$

$$\sum_{k\in\mathcal{N}_{U,i}} R_k \leq f_{B,i}(\mathbf{V}),\ i\in\mathcal{N}_R, \tag{7c}$$

$$\text{tr}\left(\mathbf{U}_k\mathbf{U}_k^\dagger\right) \leq P_{U,k},\ k\in\mathcal{N}_U, \tag{7d}$$

$$\text{tr}\left(\mathbf{V}_i\mathbf{V}_i^\dagger\right) \leq P_{R,i},\ i\in\mathcal{N}_R, \tag{7e}$$

where the conditions (7d) and (7e) impose the transmission power constraints at the UEs and RRHs, respectively.

It is difficult to find a solution of the problem (7) due to the non-convexity of the constraints (7b) and (7c). To handle the problem in a tractable manner, we adopt a change of variables as $\tilde{\mathbf{U}}_k \triangleq \mathbf{U}_k\mathbf{U}_k^\dagger$ and $\tilde{\mathbf{V}}_i \triangleq \mathbf{V}_i\mathbf{V}_i^\dagger$. Then, the problem (7) with respect the variables $\tilde{\mathbf{U}} \triangleq \{\tilde{\mathbf{U}}_k\}_{k\in\mathcal{N}_U}$ and $\tilde{\mathbf{V}} \triangleq \{\tilde{\mathbf{V}}_i\}_{i\in\mathcal{N}_R}$ with rank relaxation is a difference-of-convex (DC) problem and thus we can apply a concave convex procedure (CCCP) approach to derive an iterative algorithm that achieves monotonically non-decreasing objective values as in, e.g., [3]. The detailed algorithm is described in **Algorithm 1**, where we define the functions $\tilde{f}_{R,i}(\tilde{\mathbf{U}},\tilde{\mathbf{U}}^{(t)})$ and $\tilde{f}_{B,i}\left(\tilde{\mathbf{V}},\tilde{\mathbf{V}}^{(t)}\right)$ as

$$\tilde{f}_{R,i}\left(\tilde{\mathbf{U}},\tilde{\mathbf{U}}^{(t)}\right) \triangleq \log_2\det\left(\sum_{k\in\mathcal{N}_U\setminus\mathcal{N}_{U,i}} \bar{\mathbf{U}}_{i,k} + \mathbf{I}\right) - \varphi\left(\sum_{k\in\mathcal{N}_U\setminus\mathcal{N}_{U,i}} \bar{\mathbf{U}}_{i,k} + \mathbf{I}, \sum_{k\in\mathcal{N}_U\setminus\mathcal{N}_{U,i}} \bar{\mathbf{U}}_{i,k}^{(t)} + \mathbf{I}\right),$$

$$\tilde{f}_{B,i}\left(\tilde{\mathbf{V}},\tilde{\mathbf{V}}^{(t)}\right) \triangleq \log_2\det\left(\sum_{j\in\mathcal{N}_R} \bar{\mathbf{V}}_j + \mathbf{I}\right) - \varphi\left(\sum_{j\in\mathcal{N}_R\setminus\{i\}} \bar{\mathbf{V}}_j + \mathbf{I}, \sum_{j\in\mathcal{N}_R\setminus\{i\}} \bar{\mathbf{V}}_j^{(t)} + \mathbf{I}\right),$$

with $\bar{\mathbf{U}}_{i,k} \triangleq \mathbf{H}_{i,k}\tilde{\mathbf{U}}_k\mathbf{H}_{i,k}^\dagger$, $\bar{\mathbf{V}}_j \triangleq \mathbf{G}_j\tilde{\mathbf{V}}_j\mathbf{G}_j^\dagger$ and $\varphi(\mathbf{A},\mathbf{B}) \triangleq \log_2\det(\mathbf{B}) + \text{tr}(\mathbf{B}^{-1}(\mathbf{A}-\mathbf{B}))/\ln 2$. In the simulation, we adopted the CVX software tool in [10] to solve the convex problem (8).

The complexity of **Algorithm 1** is given as the complexity of solving the convex problem (8) at each iteration multiplied by the number of iterations. The former is known to be polynomial in the problem size (see, e.g., [11]) which is given here as $\sum_{k\in\mathcal{N}_U} n_{U,k}^2 + \sum_{i\in\mathcal{N}_R} n_{R,i}^2 + N_U$, and we observed from our simulation that the algorithm converges within a few tens of iterations.

IV. Compressed Cooperative Reception

In this section, we consider the compressed cooperative reception scheme in which the RRHs operate as compress-and-forward (CF) relays as in standard C-RAN systems [3].

Algorithm 1 CCCP algorithm for problem (7)

1. Initialize the matrices $\tilde{\mathbf{U}}^{(1)}$ and $\tilde{\mathbf{V}}^{(1)}$ to arbitrary matrices that satisfy the power constraints (7d) and (7e) and set $t=1$.
2. Update the matrices $\tilde{\mathbf{U}}^{(t+1)}$ and $\tilde{\mathbf{V}}^{(t+1)}$ as a solution of the following convex problem:

$$\underset{\tilde{\mathbf{U}},\tilde{\mathbf{V}}\succeq\mathbf{0},\mathbf{R}}{\text{maximize}} \sum_{k\in\mathcal{N}_U} R_k \tag{8a}$$

$$\text{s.t.} \sum_{k\in\mathcal{N}_{U,i}} R_k \leq \tilde{f}_{R,i}\left(\tilde{\mathbf{U}},\tilde{\mathbf{U}}^{(t)}\right),\ i\in\mathcal{N}_R, \tag{8b}$$

$$\sum_{k\in\mathcal{N}_{U,i}} R_k \leq \tilde{f}_{B,i}\left(\tilde{\mathbf{V}},\tilde{\mathbf{V}}^{(t)}\right),\ i\in\mathcal{N}_R, \tag{8c}$$

$$\text{tr}\left(\tilde{\mathbf{U}}_k\right) \leq P_{U,k},\ k\in\mathcal{N}_U, \tag{8d}$$

$$\text{tr}\left(\tilde{\mathbf{V}}_i\right) \leq P_{R,i},\ i\in\mathcal{N}_R. \tag{8e}$$

3. Stop if a convergence criterion is satisfied. Otherwise, set $t \leftarrow t+1$ and go back to Step 2.

Since the decoding of the UEs' messages is performed at the BBU based on the global observation from the RRHs, we can expect potentially better performance as compared to the DF-based per-cell reception scheme.

A. RAN Beamforming and Fronthaul Compression

As in the DF-based approach in Sec. III, each UE k first produces the encoded baseband signal $\mathbf{s}_k \in \mathbb{C}^{d_k\times 1} \sim \mathcal{CN}(\mathbf{0},\mathbf{I})$ by encoding its message M_k and performs linear beamforming as (3). After receiving the signal $\mathbf{y}_{R,i}$ in (1) on the uplink channel, RRH i performs fronthaul compression as will be described below.

We note that the goal of each RRH i in this approach is not to decode the UEs' messages but to inform the BBU of its received signal $\mathbf{y}_{R,i}$ as accurately as possible so that the BBU can perform the decoding of the messages $\{M_k\}_{k\in\mathcal{N}_U}$ based on the signals reported from the RRHs. Since the wireless fronthaul link has finite capacity, RRH i should quantize the received signal $\mathbf{y}_{R,i}$ prior to transferring to the BBU. Following, e.g., [3], we model the impact of quantization as

$$\hat{\mathbf{y}}_{R,i} = \mathbf{y}_{R,i} + \mathbf{q}_i, \tag{9}$$

where $\hat{\mathbf{y}}_{R,i}$ represents a quantized version of $\mathbf{y}_{R,i}$, and $\mathbf{q}_i$ indicates the quantization noise distributed as $\mathbf{q}_i \sim \mathcal{CN}(\mathbf{0},\mathbf{\Omega}_i)$. The decompression of the signals $\hat{\mathbf{y}}_{R,i}$ at the BBU will be discussed in Sec. IV-C.

B. Fronthaul Beamforming and Decoding

In this subsection, we discuss the conditions on the fronthaul rate C_i between the ith RRH and the BBU. Let $U_i \in \{1,\ldots,2^{nC_i}\}$ denote the index pointing the codeword $\hat{\mathbf{y}}_{R,i}$ within a quantization codebook shared between RRH i and the BBU. RRH i encodes the quantization index U_i to output the encoded signal $\mathbf{d}_i \in \mathbb{C}^{d_{f,i}\times 1} \sim \mathcal{CN}(\mathbf{0},\mathbf{I})$ which is linearly precoded as (5). Assuming that, as in Sec. III-B, the BBU decodes the messages $\{U_i\}_{i\in\mathcal{N}_R}$ from the received signal $\mathbf{y}_B$

in parallel, a rate tuple $\mathbf{C} \triangleq (C_1, \ldots, C_{N_R})$ can be achieved if the conditions $C_i \leq f_{B,i}(\mathbf{V})$ are satisfied for all $i \in \mathcal{N}_R$.

C. Fronthaul Decompression and RAN Decoding

It was shown in [12, Ch. 3] that the BBU can successfully decompress the quantized signals $\hat{\mathbf{y}}_{R,1}, \ldots, \hat{\mathbf{y}}_{R,N_R}$ from the decoded messages $\{U_i\}_{i\in\mathcal{N}_R}$ if the conditions

$$g_i(\mathbf{U}, \mathbf{\Omega}) \triangleq I(\mathbf{y}_{R,i}; \hat{\mathbf{y}}_{R,i}) \quad (10)$$
$$= \Phi\left(\sum_{k\in\mathcal{N}_U} \mathcal{T}(\mathbf{H}_{i,k}\mathbf{U}_k) + \mathbf{I}, \mathbf{\Omega}_i\right) \leq C_i$$

are satisfied for all $i \in \mathcal{N}_R$, where we define the notation $\mathbf{\Omega} \triangleq \{\mathbf{\Omega}_i\}_{i\in\mathcal{N}_R}$.

Afterward, we assume that the BBU decodes the messages $\{M_k\}_{k\in\mathcal{N}_U}$ sent by the UEs based on the decompressed signals $\{\hat{\mathbf{y}}_{R,i}\}_{i\in\mathcal{N}_R}$ without SIC so that the maximum rate R_k achievable for the kth UE is given as

$$R_k = f_{U,k}(\mathbf{U}, \mathbf{\Omega}) \triangleq I(\mathbf{s}_k; \{\hat{\mathbf{y}}_{R,i}\}_{i\in\mathcal{N}_R}) \quad (11)$$
$$= \Phi\left(\mathcal{T}\left(\tilde{\mathbf{H}}_k\mathbf{U}_k\right), \sum_{l\in\mathcal{N}_U\setminus\{k\}} \mathcal{T}\left(\tilde{\mathbf{H}}_l\mathbf{U}_l\right) + \bar{\mathbf{\Omega}} + \mathbf{I}\right),$$

where we define the matrices $\tilde{\mathbf{H}}_k \triangleq [\mathbf{H}_{1,k}^\dagger \ldots \mathbf{H}_{N_R,k}^\dagger]^\dagger$ and $\bar{\mathbf{\Omega}} \triangleq \mathrm{diag}(\mathbf{\Omega}_1, \ldots, \mathbf{\Omega}_{N_R})$.

D. Problem Definition and Optimization

As in Sec. III-C, we aim at jointly optimizing the fronthaul beamforming $\mathbf{V}$, the RAN beamforming $\mathbf{U}$ and the fronthaul compression strategies $\mathbf{\Omega}$ with the goal of maximizing the sum-rate $\sum_{k\in\mathcal{N}_U} R_k$ subject to the per-UE and per-RRH power constraints. The problem can be stated as

$$\underset{\mathbf{V},\mathbf{U},\mathbf{\Omega}\succeq\mathbf{0},\mathbf{C}}{\mathrm{maximize}} \sum_{k\in\mathcal{N}_U} f_{U,k}(\mathbf{U}, \mathbf{\Omega}) \quad (12a)$$
$$\text{s.t. } C_i \leq f_{B,i}(\mathbf{V}), \ i \in \mathcal{N}_R, \quad (12b)$$
$$g_i(\mathbf{U}, \mathbf{\Omega}) \leq C_i, \ i \in \mathcal{N}_R, \quad (12c)$$
$$\mathrm{tr}\left(\mathbf{U}_k\mathbf{U}_k^\dagger\right) \leq P_{U,k}, \ k \in \mathcal{N}_U, \quad (12d)$$
$$\mathrm{tr}\left(\mathbf{V}_i\mathbf{V}_i^\dagger\right) \leq P_{R,i}, \ i \in \mathcal{N}_R. \quad (12e)$$

We note that, as for (7), we can adopt a change of variables $\tilde{\mathbf{U}}_k \triangleq \mathbf{U}_k\mathbf{U}_k^\dagger$ and $\tilde{\mathbf{V}}_i \triangleq \mathbf{V}_i\mathbf{V}_i^\dagger$ to obtain a DC problem with rank relaxation. Therefore, we can derive a CCCP-based iterative algorithm as described in **Algorithm 2** that guarantees monotonically non-decreasing objective values. In the algorithm, we define the functions

$$\tilde{f}_{U,k}\left(\tilde{\mathbf{U}}, \mathbf{\Omega}, \tilde{\mathbf{U}}^{(t)}, \mathbf{\Omega}^{(t)}\right) \triangleq \log_2\det\left(\sum_{l\in\mathcal{N}_U} \bar{\mathbf{U}}_l + \bar{\mathbf{\Omega}} + \mathbf{I}\right)$$
$$-\varphi\left(\sum_{l\in\mathcal{N}_U\setminus\{k\}} \bar{\mathbf{U}}_l + \bar{\mathbf{\Omega}} + \mathbf{I}, \sum_{l\in\mathcal{N}_U\setminus\{k\}} \bar{\mathbf{U}}_l^{(t)} + \bar{\mathbf{\Omega}}^{(t)} + \mathbf{I}\right),$$

Algorithm 2 CCCP algorithm for problem (12)

1. Initialize the matrices $\tilde{\mathbf{U}}^{(1)}$, $\mathbf{\Omega}^{(1)}$ and $\tilde{\mathbf{V}}^{(1)}$ to arbitrary matrices that satisfy the power constraints (7d) and (7e) and set $t = 1$.

2. Update the matrices $\tilde{\mathbf{U}}^{(t+1)}$, $\mathbf{\Omega}^{(t+1)}$ and $\tilde{\mathbf{V}}^{(t+1)}$ as a solution of the following convex problem:

$$\underset{\tilde{\mathbf{V}},\tilde{\mathbf{U}},\mathbf{\Omega}\succeq\mathbf{0},\mathbf{C}}{\mathrm{maximize}} \sum_{k\in\mathcal{N}_U} \tilde{f}_{U,k}\left(\tilde{\mathbf{U}}, \mathbf{\Omega}, \tilde{\mathbf{U}}^{(t)}, \mathbf{\Omega}^{(t)}\right) \quad (13a)$$
$$\text{s.t. } C_i \leq \tilde{f}_{B,i}\left(\tilde{\mathbf{V}}\right), \ i \in \mathcal{N}_R, \quad (13b)$$
$$\tilde{g}_i\left(\tilde{\mathbf{U}}, \mathbf{\Omega}, \tilde{\mathbf{U}}^{(t)}, \mathbf{\Omega}^{(t)}\right) \leq C_i, \ i \in \mathcal{N}_R, \quad (13c)$$
$$\mathrm{tr}\left(\tilde{\mathbf{U}}_k\right) \leq P_{U,k}, \ k \in \mathcal{N}_U, \quad (13d)$$
$$\mathrm{tr}\left(\tilde{\mathbf{V}}_i\right) \leq P_{R,i}, \ i \in \mathcal{N}_R. \quad (13e)$$

3. Stop if a convergence criterion is satisfied. Otherwise, set $t \leftarrow t + 1$ and go back to Step 2.

and

$$\tilde{g}_i\left(\tilde{\mathbf{U}}, \mathbf{\Omega}, \tilde{\mathbf{U}}^{(t)}, \mathbf{\Omega}^{(t)}\right) \triangleq -\log_2\det(\mathbf{\Omega}_i),$$
$$+\varphi\left(\sum_{k\in\mathcal{N}_U} \bar{\mathbf{U}}_{i,k} + \mathbf{I} + \mathbf{\Omega}_i, \sum_{k\in\mathcal{N}_U} \bar{\mathbf{U}}_{i,k}^{(t)} + \mathbf{I} + \mathbf{\Omega}_i^{(t)}\right)$$

with $\bar{\mathbf{U}}_l \triangleq \tilde{\mathbf{H}}_l\tilde{\mathbf{U}}_l\tilde{\mathbf{H}}_l^\dagger$ and $\bar{\mathbf{U}}_{i,k} \triangleq \mathbf{H}_{i,k}\tilde{\mathbf{U}}_k\mathbf{H}_{i,k}^\dagger$.

Similar to the discussion in Sec. III-C, the complexity of **Algorithm 2** is given as the product of the complexity of solving (13) and the number of iterations, where the former is polynomial in the problem size $N_U n_R^2 + \sum_{i\in\mathcal{N}_R} 2n_{R,i}^2 + N_R$ and the latter was observed from our simulation to be less than 100.

V. Numerical Results

In this section, we present some numerical results that validate the advantages of the CF-based cooperative reception scheme (Sec. IV) compared to the DF-based per-cell approach (Sec. III). For the CF-based cooperative scheme, in addition to the joint optimization of the access and fronthaul links according to **Algorithm 2**, we also show the performance obtained with a separate design in which the fronthaul beamforming matrices $\mathbf{V}$ are first optimized with the criterion of maximizing the minimum fronthaul capacity $C_{\min} \triangleq \min_{i\in\mathcal{N}_R} C_i$, and then the other variables $\mathbf{U}$ and $\mathbf{\Omega}$ are optimized. In the simulation, we assume that the locations of the RRHs and UEs are determined from a uniform distribution within a $500\text{m} \times 500\text{m}$ rectangular area, while the BBU is located at the center of the cluster. We consider the channel model $\mathbf{H}_{i,k} = \sqrt{\gamma_{i,k}}\tilde{\mathbf{H}}_{i,k}$ of the access link, where the path-loss $\gamma_{i,k}$ is obtained as $\gamma_{i,k} = 1/(1 + (d_{i,k}/d_0)^\alpha)$ with the distance $d_{i,k}$ between the RRH i and UE k. The path-loss exponent and the reference distance are set to $\alpha = 3$ and $d_0 = 80$m, respectively. The elements of $\tilde{\mathbf{H}}_{i,k}$ are independent and identically distributed (i.i.d.) as $\mathcal{CN}(0, 1)$. The channel matrices $\mathbf{G}_i$ for the fronthaul link are similarly defined.

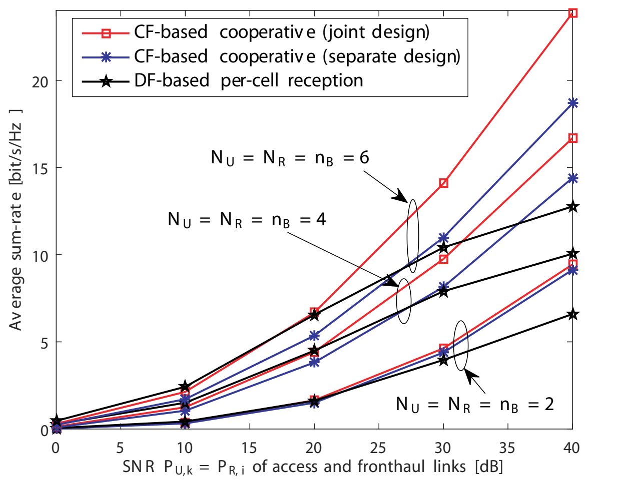

Figure 2. Average sum-rate versus the SNR $P_{U,k} = P_{R,i}$ of the access and fronthaul links for a C-RAN uplink ($N_U = N_R = n_B \in \{2, 4, 6\}$ and $n_{U,k} = n_{R,i} = 1$).

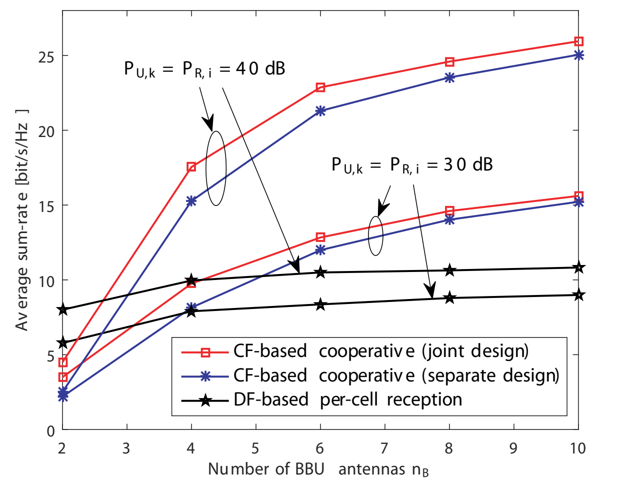

Figure 3. Average sum-rate versus the number n_B of BBU antennas for a C-RAN uplink ($N_U = N_R = 4$, $n_{U,k} = n_{R,i} = 1$ and $P_{U,k} = P_{R,i} \in \{30, 40\}$ dB).

Fig. 2 shows the impact of the SNR $P_{U,k} = P_{R,i}$ of the access and fronthaul links on the average sum-rate performance for a C-RAN with $N_U = N_R = n_B \in \{2, 4, 6\}$ and $n_{U,k} = n_{R,i} = 1$. We observe a promising result that the CF-based cooperative scheme is capable of achieving a significant performance gain over the DF-based single-cell approach even with unreliable wireless fronthaul links. Also, the gain is more pronounced as the system size $N_U = N_R = n_B$ increases due to the increased number of interference signals both in the access and fronthaul links. Specifically, the gain amounts to about 87 % at the SNR of 40 dB and with $N_U = N_R = n_B = 6$. It is also worth noting that, comparing the performance of the joint and separate designs of the CF-based scheme, the importance of the joint design becomes more significant when the SNR is larger or the system size increases. This observation coincides with the results reported in [7] for the downlink of C-RAN.

In Fig. 3, we plot the average sum-rate versus the number n_B of BBU antennas for the uplink of a C-RAN with $N_U = N_R = n_B = 4$, $n_{U,k} = n_{R,i} = 1$ and $P_{U,k} = P_{R,i} \in \{30, 40\}$ dB. It is observed from the figure that, when the fronthaul link is not reliable with a small n_B, the advantage of the CF-based cooperation is defeated by the impact of the quantization noise power. However, as the number n_B increases, the performance gain of the CF-based scheme over the DF-based per-cell reception becomes significant. It is also noted that the CF-based scheme with the separate design of the access and fronthaul links shows performance approaching that of the joint design as we increase the number n_B.

VI. Conclusion

We have studied a joint design of radio access and wireless fronthaul links for the uplink of a C-RAN system. We have tackled the sum-rate maximization problem under the assumptions of DF-based per-cell reception and CF-based cooperative reception schemes. For the both problems, we have derived CCCP-based iterative algorithms that achieve monotonically non-decreasing sum-rates. Via link-level simulation results, we have confirmed that the cooperative reception scheme can significantly outperform the conventional per-cell reception scheme.

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