Joint Design of Fronthaul and Access Links for C-RAN With Wireless Fronthauling

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***Abstract*—This letter studies a joint design of fronthaul and radio access links for a cloud radio access network (C-RAN) with wireless fronthauling, where a baseband unit (BBU) controls a number of remote radio heads (RRHs) via wireless fronthaul links to communicate with user equipments. We first review a basic approach based on a single cell concept, whereby the RRHs operate as decode-and-forward (DF) relays. Then, a cooperative transmission from the RRHs based on decompress-and-forward (DCF) relaying is proposed, which is a standard concept in C-RAN. For both strategies, a problem of jointly optimizing the BBU and RRH operations is tackled with the goal of maximizing the weighted sum-rate subject to the BBU and per-RRH power constraints. For each formulated problem, an iterative algorithm is derived that achieves a sequence of monotonically nondecreasing objective values at each iteration. It is confirmed via numerical results that the DCF-based cooperative scheme significantly outperforms the DF-based single-cell approach.**

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

I. Introduction

Cloud radio access network (C-RAN) is a promising structure for the fifth generation wireless systems due to its potential advantages of reducing capital and operating expenditures and of providing high spectral efficiency by means of interference management capabilities [1], [2]. Specifically, the latter can be made possible by migrating the baseband processing functionalities to a baseband processing unit (BBU) that is connected to a number of remote radio heads (RRHs) through fronthaul links. However, it has been reported that the fronthaul links may be a bottleneck of the system due to high bit rate requirement of the quantized IQ samples [1], [3]. Traditionally, the backhaul or the fronthaul has been modeled as wired digital links of infinite or fixed capacities in literatures [4]–[7]. In contrast, in this letter, we consider a wireless fronthaul network motivated by practical constraints and rapidly increasing interest on cost-effective wireless fronthaul [9]–[11]. Despite of its importance, relatively little works have focused on C-RAN systems with wireless fronthaul links.

We study the downlink of a C-RAN, where the BBU communicates with the RRHs via wireless fronthaul links. We consider two different strategies depending on the type of relaying operations at the RRHs, namely decode-and-forward (DF) based single-cell approach and decompress-and-forward (DCF) based cooperative scheme. In the DF-based scheme, each RRH processes its received baseband signal[1] to decode the messages intended for user equipments (UEs) located within its coverage. Then, based on the decoded messages, the RRH performs local, or single-cell, beamforming [4], [5]. The optimization of this approach requires an exhaustive discrete search to find an optimal cell association. Even if the optimal association is made, it may suffer from intercell interference, which becomes significant particularly with a large number of UEs and high signal-to-noise ratio (SNR).

In contrast, in the DCF-based cooperative scheme [6], [7], the BBU performs clustered linear beamforming across the RRHs to enable effective interference management. Afterwards, the beamforming output signals are quantized and compressed prior to transferring to the RRHs on the wireless fronthaul links. Since we assume a wireless fronthaul network, the capacities of the fronthaul links are also included in the optimization space unlike the previous works [6], [7] in which the fronthaul links were assumed to have fixed capacities. For the two approaches discussed above, we tackle the problem of jointly optimizing the BBU and RRH operations with the goal of maximizing a weighted sum of per-UE rates subject to the BBU and per-RRH power constraints. We propose iterative algorithms based on the difference-of-convex (DC) programming approach, and confirm via numerical results that the DCF-based cooperative scheme shows a performance gain of 70.3% compared to the DF-based single-cell approach.

II. System Model

We consider the downlink of a C-RAN, where a BBU sends independent messages to N_U multiantenna UEs by controlling N_R multiantenna RRHs through wireless fronthaul links. We

[1]Note that, in order to implement the digital fronthaul approach in the wireless fronthaul links [8], unlike the conventional C-RAN systems, RRHs need to perform baseband processing for the fronthaul communication.

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assume that the BBU, RRH i ($i \in \mathcal{N}_R$), and UE k ($k \in \mathcal{N}_U$) use n_B, $n_{R,i}$, and $n_{U,k}$ antennas, respectively, and define the total number of RRH antennas as $n_R \triangleq \sum_{i\in\mathcal{N}_R} n_{R,i}$. Here the sets of the RRHs and the UEs are denoted as $\mathcal{N}_R \triangleq \{1,\ldots,N_R\}$ and $\mathcal{N}_U \triangleq \{1,\ldots,N_U\}$, respectively.

The BBU first generates independent messages $M_k \in \{1,\ldots,2^{nR_k}\}$ to be communicated to UE k for $k \in \mathcal{N}_U$, where n stands for a coding block length assumed to be large, and R_k equals the rate of the message M_k. We assume that the fronthaul and access links are separated in the frequency or time domain, and thus do not interfere with each other.

In a coherent fronthaul network, it is assumed that the wireless communications from the BBU to the RRHs take place at the same frequency/time resource. The signal $\mathbf{y}_{R,i} \in \mathbb{C}^{n_{R,i}\times 1}$ received by the ith RRH is then given by

$$\mathbf{y}_{R,i} = \mathbf{H}_i\mathbf{x}_B + \mathbf{z}_{R,i} \tag{1}$$

where $\mathbf{x}_B \in \mathbb{C}^{n_B\times 1}$ is the signal transmitted by the BBU, $\mathbf{H}_i \in \mathbb{C}^{n_{R,i}\times n_B}$ represents the channel response matrix from the BBU to RRH i, and $\mathbf{z}_{R,i} \sim \mathcal{CN}(\mathbf{0},\mathbf{I})$ indicates the additive noise at RRH i. For a fair comparison among different schemes, we impose transmission power constraint at the BBU as $\mathbb{E}||\mathbf{x}_B||^2 \leq P_B$.

Each RRH i processes the received signal $\mathbf{y}_{R,i}$ to produce the signal $\mathbf{x}_{R,i} \in \mathbb{C}^{n_{R,i}\times 1}$ to be transmitted in the downlink. The signal $\mathbf{y}_{U,k} \in \mathbb{C}^{n_{U,k}\times 1}$ received by UE k is denoted as

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

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

III. DF-Based Single-Cell Processing

This section considers the RRHs operating as DF relays as in traditional single-cell systems. To this end, the set $\mathcal{N}_U$ of UEs is partitioned into N_R disjoint sets $\mathcal{N}_{U,1},\ldots,\mathcal{N}_{U,N_R}$, i.e., $\mathcal{N}_{U,i} \cap \mathcal{N}_{U,j} = \emptyset$ for all $i \neq j \in \mathcal{N}_R$ and $\sum_{i\in\mathcal{N}_R} \mathcal{N}_{U,i} = \mathcal{N}_U$, where the UEs in each set $\mathcal{N}_{U,i}$ are served by RRH i. The task of determining the partitioning $\mathcal{N}_{U,1},\ldots,\mathcal{N}_{U,N_R}$ is typically referred to as *cell association* [4]. The following sections discuss two-phase operations carried out after the cell association is given.

A. Fronthaul Beamforming

The goal of this phase is to inform each RRH i of the set $Q_i \triangleq \{M_k\}_{k\in\mathcal{N}_{U,i}}$ of messages intended for the UEs $\mathcal{N}_{U,i}$ served by the RRH. To this end, the BBU encodes the message Q_i to obtain the encoded baseband signal $\mathbf{d}_i \in \mathbb{C}^{d_{f,i}\times 1} \sim \mathcal{CN}(\mathbf{0},\mathbf{I})$, and then linear beamforming is applied on the signal $\mathbf{d}_i$ to generate the transmitted signal

$$\mathbf{x}_B = \sum_{i\in\mathcal{N}_R} \mathbf{V}_i\mathbf{d}_i \tag{3}$$

where $\mathbf{V}_i \in \mathbb{C}^{n_B\times d_{f,i}}$ denotes the beamforming matrix for $\mathbf{d}_i$. With (3), the received signal (1) can be written as

$$\mathbf{y}_{R,i} = \mathbf{H}_i\mathbf{V}_i\mathbf{d}_i + \sum_{j\in\mathcal{N}_R\setminus\{i\}} \mathbf{H}_i\mathbf{V}_j\mathbf{d}_j + \mathbf{z}_{R,i} \tag{4}$$

where the first term represents the desired signal to be decoded by the receiving RRH.

Assuming that RRH i decodes the message Q_i which contains $\{M_k\}_{k\in\mathcal{N}_{U,i}}$ based on its received signal $\mathbf{y}_{R,i}$, the sum-rate $\sum_{k\in\mathcal{N}_{U,i}} R_k$ of the messages $\{M_k\}_{k\in\mathcal{N}_{U,i}}$ is bounded on the fronthaul link as

$$\begin{aligned}\sum_{k\in\mathcal{N}_{U,i}} R_k &\leq f_{\text{front},i}(\mathbf{V}) \triangleq I(\mathbf{d}_i;\mathbf{y}_{R,i})\\ &= \Phi\left(\mathcal{T}(\mathbf{H}_i\mathbf{V}_i),\ \sum_{j\in\mathcal{N}_R\setminus\{i\}}\mathcal{T}(\mathbf{H}_i\mathbf{V}_j)+\mathbf{I}\right)\end{aligned} \tag{5}$$

where we define $\mathcal{T}(\mathbf{X}) \triangleq \mathbf{X}\mathbf{X}^\dagger$ 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. Per-RRH Local Beamforming

In the next phase, RRH i performs channel encoding on the decoded messages $\{M_k\}_{k\in\mathcal{N}_{U,i}}$ to obtain the encoded baseband signals $\mathbf{s}_k \in \mathbb{C}^{d_k\times 1} \sim \mathcal{CN}(\mathbf{0},\mathbf{I})$ for $k \in \mathcal{N}_{U,i}$, and linear beamforming is applied as

$$\mathbf{x}_{R,i} = \sum_{k\in\mathcal{N}_{U,i}} \mathbf{U}_k\mathbf{s}_k \tag{6}$$

where $\mathbf{U}_k \in \mathbb{C}^{n_{R,i}\times d_k}$ denotes the beamforming matrix for UE k. Note that the beamforming model (6) prescribes that macrodiversity is not utilized since the signal intended for each UE is emitted by only one RRH.

Assuming that UE k decodes the message M_k based on the received signal $\mathbf{y}_{U,k}$, the rate R_k of the message M_k is constrained as

$$\begin{aligned}R_k &\leq f_{\text{access},k}(\mathbf{U}) \triangleq I(\mathbf{s}_k;\mathbf{y}_{U,k})\\ &= \Phi\left(\mathcal{T}(\mathbf{G}_{k,i}\mathbf{U}_l),\ \sum_{(j,l)\neq(i,k)}\mathcal{T}(\mathbf{G}_{k,j}\mathbf{U}_l)+\mathbf{I}\right).\end{aligned} \tag{7}$$

C. Problem Definition and Optimization

We aim at maximizing the weighted sum-rate $\sum_{k\in\mathcal{N}_U} w_k R_k$ while satisfying the BBU and per-RRH power constraints. The problem is stated as

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

$$\text{s.t.} \sum_{k\in\mathcal{N}_{U,i}} R_k \leq f_{\text{front},i}(\mathbf{V}),\ i\in\mathcal{N}_R \tag{8b}$$

$$R_k \leq f_{\text{access},k}(\mathbf{U}),\ k\in\mathcal{N}_U \tag{8c}$$

$$\sum_{i\in\mathcal{N}_R} \text{tr}\left(\mathbf{V}_i\mathbf{V}_i^\dagger\right) \leq P_B \tag{8d}$$

$$\sum_{k\in\mathcal{N}_{U,i}} \text{tr}\left(\mathbf{U}_k\mathbf{U}_k^\dagger\right) \leq P_{R,i},\ i\in\mathcal{N}_R \tag{8e}$$

[2]We assume that the system operates in a time-division duplex mode, so that the channel matrices $\{\mathbf{H}_i\}_{i\in\mathcal{N}_R}$ for the fronthaul link are estimated by the BBU using reciprocity. Similarly, the channel matrices $\{\mathbf{G}_{k,i}\}_{k\in\mathcal{N}_U}$ between the ith RRH and the UEs are estimated by the ith RRH using the reciprocity and reported to the BBU via the fronthaul link.

where the constraints (8b) and (8c) come from (5) and (7), respectively, and the conditions (8d) and (8e) represent the transmit power constraints.

Since it is difficult to solve problem (8) due to nonconvexity in (8b) and (8c), as in [7, Sec. V], we tackle the problem in terms of the transformed variables $\tilde{\mathbf{V}}_i \triangleq \mathbf{V}_i\mathbf{V}_i^\dagger$ and $\tilde{\mathbf{U}}_k \triangleq \mathbf{U}_k\mathbf{U}_k^\dagger$, which yield a DC problem with rank relaxation. Thus, we can apply the DC programming approach to the obtained problem to achieve a sequence of monotonically nondecreasing objective values at each iteration. It is known that the DC-based iterative algorithm converges to a critical point of the original problem [12], [13]. The complexity of the algorithm is given as the product of the number of iterations and the complexity of solving convex problems at each iteration. In our simulations, the convergence is achieved within a few tens of iterations. The complexity of solving a convex problem is known to be polynomial in the problem size, which is here given as $N_R n_B^2 + N_U(\tilde{n}_R^2+1)$ assuming $n_{R,i} = \tilde{n}_R$ for all $i \in \mathcal{N}_R$, since the optimization (8) is with respect to the variables $\{\tilde{\mathbf{V}}_i\}_{i\in\mathcal{N}_R}$, $\{\tilde{\mathbf{U}}_k\}_{k\in\mathcal{N}_U}$ and $\{R_k\}_{k\in\mathcal{N}_U}$.

IV. DCF-Based Cooperative Scheme

In this section, we assume that the RRHs operate as in standard C-RAN architecture [7] such that the BBU quantizes and compresses the linearly precoded signals prior to transferring to the RRHs on the wireless fronthaul links, and each RRH recovers the quantized signal and transmits it in the downlink.

A. Fronthaul Beamforming

Similar to the first phase of the DF strategy described in Section III-A, the BBU manages the operations of the RRHs on the wireless fronthaul links by sending a message $U_i \in \{1,\ldots,2^{nC_i}\}$ to RRH i for $i \in \mathcal{N}_R$. Here C_i denotes the rate of the message U_i and can be regarded as the capacity of the fronthaul link connecting to RRH i. Note that in the previous work [7], C_i was a fixed value. In contrast, in this letter, the optimization space also includes the fronthaul capacity parameters $\mathbf{C} \triangleq \{C_i\}_{i\in\mathcal{N}_R}$ which are determined by the fronthaul beamforming strategy described below.

The BBU first encodes each message U_i to obtain the $d_{f,i}$-dimensional encoded baseband signal $\mathbf{d}_i \sim \mathcal{CN}(\mathbf{0},\mathbf{I})$, and forms the transmitted signal $\mathbf{x}_B$ by linear beamforming (3). The signal $\mathbf{y}_{R,i}$ received at RRH i can then be written as (4). Assuming that RRH i performs decoding on the message U_i based on (4), the rate C_i is achievable if the condition

$$C_i \le f_{\text{front},i}(\mathbf{V}) \tag{9}$$

is satisfied with the function $f_{\text{front},i}(\mathbf{V})$ defined in (5).

B. Clustered Beamforming and Fronthaul Compression

Suppose that the fronthaul beamforming $\mathbf{V}$ and the capacities $\mathbf{C}$ are given. Then, we obtain the same system model as in [6] and [7] where the messages U_i are used to indicate the quantized versions of the beamforming output signals. The BBU encodes the messages M_k to produce the encoded signals $\mathbf{s}_k \sim \mathcal{CN}(\mathbf{0},\mathbf{I})$ for $k \in \mathcal{N}_U$, that are linearly precoded as

$$\tilde{\mathbf{x}}_R = \sum_{k\in\mathcal{N}_U} \mathbf{L}_k\mathbf{s}_k \tag{10}$$

where $\mathbf{L}_k$ represents the beamforming matrix for the signal $\mathbf{s}_k$. Note that the goal of the linear beamforming (10), referred to as *clustered beamforming*, is to achieve macro-diversity over the cluster $\mathcal{N}_R$ of the RRHs, which is not possible with the DF strategy in Section III.

Since the fronthaul links have finite capacities $\mathbf{C}$, the BBU quantizes and compresses the precoded signals to generate the compression indices $U_1,\ldots,U_{N_R}$, where each index $U_i \in \{1,\ldots,2^{nC_i}\}$ points to the quantized version $\mathbf{x}_{R,i}$ of the signal $\tilde{\mathbf{x}}_{R,i} \in \mathbb{C}^{n_{R,i}\times 1}$ which equals the ith subvector of $\tilde{\mathbf{x}}_R$, i.e., $\tilde{\mathbf{x}}_R = [\tilde{\mathbf{x}}_{R,1}^\dagger \ldots \tilde{\mathbf{x}}_{R,N_R}^\dagger]^\dagger$. Following the works [6] and [7], we assume that the quantized signal $\mathbf{x}_{R,i}$, that is to be transferred to RRH i, is modeled as

$$\mathbf{x}_{R,i} = \tilde{\mathbf{x}}_{R,i} + \mathbf{q}_i \tag{11}$$

where the quantization noise $\mathbf{q}_i$ is independent of the signal $\tilde{\mathbf{x}}_{R,i}$ and distributed as $\mathbf{q}_i \sim \mathcal{CN}(\mathbf{0},\mathbf{\Omega}_i)$ with $\mathbf{\Omega}_i \triangleq \mathbb{E}[\mathbf{q}_i\mathbf{q}_i^\dagger] \succeq \mathbf{0}$. We assume that, as in [6], the signals $\tilde{\mathbf{x}}_{R,1},\ldots,\tilde{\mathbf{x}}_{R,N_R}$ are compressed independently so that the quantization noise signals $\mathbf{q}_i$ and $\mathbf{q}_j$ of different RRHs ($i \neq j$) are uncorrelated, i.e., $\mathbb{E}[\mathbf{q}_i\mathbf{q}_j^\dagger] = \mathbf{0}$. For notational convenience, we define $\mathbf{q} \triangleq [\mathbf{q}_1^\dagger \ldots \mathbf{q}_{N_R}^\dagger]^\dagger \sim \mathcal{CN}(\mathbf{0},\bar{\mathbf{\Omega}})$ with covariance matrix $\bar{\mathbf{\Omega}} \triangleq \text{diag}(\mathbf{\Omega}_1,\ldots,\mathbf{\Omega}_{N_R})$. It was shown in [14, Ch. 3] that the signal $\mathbf{x}_{R,i}$ can be recovered by RRH i if the condition

$$g_i(\mathbf{L},\mathbf{\Omega}) \triangleq I(\tilde{\mathbf{x}}_R;\mathbf{x}_{R,i}) = \Phi\left(\sum_{k\in\mathcal{N}_U}\mathcal{T}(\mathbf{E}_i^\dagger\mathbf{L}_k),\mathbf{\Omega}_i\right) \le C_i \tag{12}$$

is satisfied. Here we define the matrix $\mathbf{E}_i \in \mathbb{C}^{n_R\times n_{R,i}}$ having all-zero elements except for the rows from $(\sum_{j=1}^{i-1} n_{R,j}+1)$ to $(\sum_{j=1}^{i} n_{R,j})$ being identity matrix of size $n_{R,i}$.

After recovering the baseband signal $\mathbf{x}_{R,i}$ based on the index U_i which is decoded from the received signal $\mathbf{y}_{R,i}$, RRH i upconverts and transmits the signal $\mathbf{x}_{R,i}$ in the downlink channel. Assuming that UE k decodes the message M_k based on the signal $\mathbf{y}_{U,k}$, the rate R_k of the message can be achieved if the following condition is satisfied:

$$\begin{aligned} R_k \le f_k(\mathbf{L},\mathbf{\Omega}) &\triangleq I(\mathbf{s}_k;\mathbf{y}_{U,k}) \\ &= \Phi\left(\mathcal{T}(\mathbf{G}_k\mathbf{L}_k),\ \sum_{l\in\mathcal{N}_U\setminus\{k\}}\mathcal{T}(\mathbf{G}_k\mathbf{L}_l) + \mathbf{G}_k\bar{\mathbf{\Omega}}\mathbf{G}_k^\dagger + \mathbf{I}\right) \end{aligned} \tag{13}$$

where we defined the channel matrix $\mathbf{G}_k \triangleq [\mathbf{G}_{k,1},\ldots,\mathbf{G}_{k,N_R}]$ from all the RRHs to UE k.

C. Problem Definition and Optimization

As in Section III-C, we aim at jointly optimizing the fronthaul beamforming $\mathbf{V}$, the clustered beamforming $\mathbf{L}$ and the fronthaul compression strategies $\mathbf{\Omega}$ with the goal of maximizing the weighted sum-rate subject to the BBU and per-RRH power constraints. The problem can be formulated as

$$\underset{\mathbf{V},\mathbf{L},\mathbf{\Omega}\succeq\mathbf{0},\mathbf{C}}{\text{maximize}} \sum_{k\in\mathcal{N}_U} w_k f_k(\mathbf{L},\mathbf{\Omega}) \tag{14a}$$

$$\text{s.t.}\quad C_i \le f_{\text{front},i}(\mathbf{V}),\ i\in\mathcal{N}_R \tag{14b}$$

$$g_i(\mathbf{L},\mathbf{\Omega}) \le C_i,\ i\in\mathcal{N}_R \tag{14c}$$

$$\sum_{i\in\mathcal{N}_R}\text{tr}\left(\mathbf{V}_i\mathbf{V}_i^\dagger\right) \le P_B \tag{14d}$$

$$\sum_{k\in\mathcal{N}_U}\text{tr}\left(\mathbf{E}_i^\dagger\mathbf{L}_k\mathbf{L}_k^\dagger\mathbf{E}_i\right) + \text{tr}(\mathbf{\Omega}_i) \le P_{R,i},\ i\in\mathcal{N}_R.$$

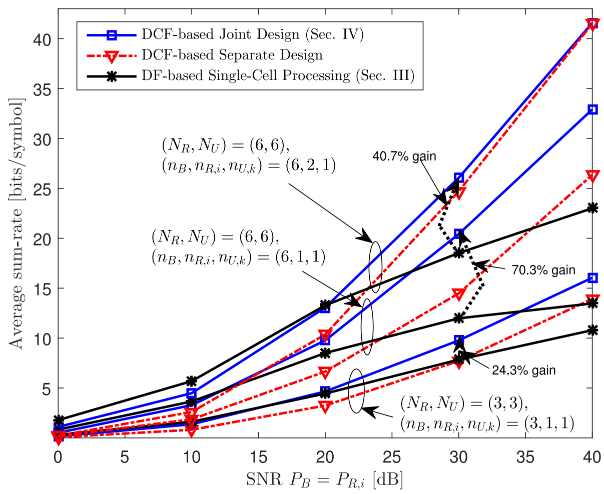

Fig. 1. Average sum-rate versus the SNRs $P_B = P_{R,i}$ of the fronthaul and access links for a C-RAN with $N_R = N_U \in \{3, 6\}$, $n_{R,i} \in \{1, 2\}$ and $n_{U,k} = 1$.

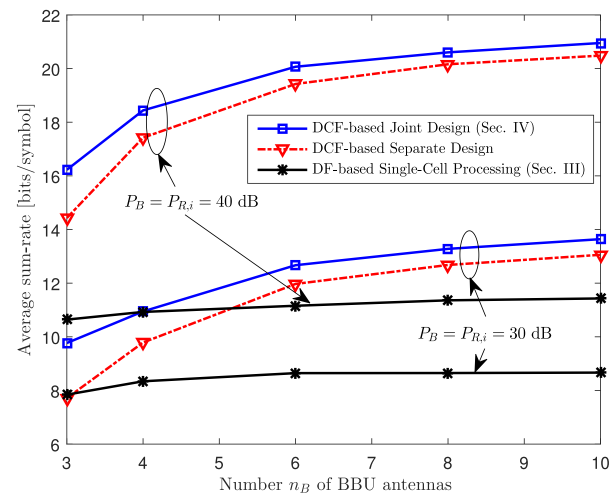

Fig. 2. Average sum-rate versus the number n_B of BBU antennas for a C-RAN with $N_R = N_U = 3$, $n_{R,i} = n_{U,k} = 1$ and $P_B = P_{R,i} \in \{30, 40\}$ dB.

Note that problem (14) is also nonconvex due to the objective function (14a) and the constraints (14b) and (14c). We instead tackle the problem with respect to the variables $\tilde{\mathbf{V}}_i \triangleq \mathbf{V}_i\mathbf{V}_i^\dagger$ and $\tilde{\mathbf{L}}_k \triangleq \mathbf{L}_k\mathbf{L}_k^\dagger$, which is again a DC problem with rank relaxation. Thus, we can apply the DC programming approach of [12] for problem (14). We remark that the optimization with the multivariate compression scheme [7], in which the signals for different RRHs are jointly compressed, can be similarly addressed as discussed in [7, Sec. V] under fixed-capacity fronthaul links. As in Section III-C, for the single-cell processing, the complexity is given as the number of iterations multiplied by the complexity of solving the convex problems at each iteration, which is polynomial in the problem size given as $N_R n_B^2 + N_U n_R^2 + N_R \tilde{n}_R^2 + N_R$.

V. Numerical Results

Fig. 1 illustrates the average sum-rate with $w_k = 1$ for all $k \in \mathcal{N}_U$ in terms of SNRs $P_B = P_{R,i}$ of the fronthaul and access links for a C-RAN with $N_R = N_U \in \{3, 6\}$, $n_{R,i} \in \{1, 2\}$, and $n_{U,k} = 1$. We compare the performance of the DF-based single-cell processing (see Section III) and DCF-based cooperative scheme (see Section IV) under the assumption that the locations of the RRHs and UEs are determined from a uniform distribution within a square area of side length 500 m, while the BBU is located at the center of the cell. We consider an independent and identically distributed (i.i.d.) Rayleigh fading channel with the path-loss model given as $1/(1 + (d/d_0)^\alpha)$, where d represents the distance and we set $\alpha = 3$ and $d_0 = 80$ m. We focus on the case where the channel matrices are perfectly known to the BBU and there is no other-cluster interference (OCI) from the adjacent clusters.[3] For reference, we also present the performance of the case where the fronthaul and access links of the DCF scheme are separately optimized. In this case, the fronthaul beamforming matrices $\mathbf{V}$ are optimized to maximize the minimum fronthaul capacity $C_{\min} \triangleq \min_{i\in\mathcal{N}_R} C_i$, and then the clustered beamforming $\mathbf{L}$ and the fronthaul compression strategies $\mathbf{\Omega}$ are jointly optimized for fixed fronthaul capacities $\mathbf{C}$. For the DF scheme, the partitioning $\mathcal{N}_{U,1}, \ldots, \mathcal{N}_{U,N_R}$ for cell association is determined such that each UE k is served by RRH i with the largest channel gain $||\mathbf{G}_{k,i}||_F^2$.

It is observed that the DCF-based cooperative scheme with joint processing across the RRHs outperforms the DF-based single-cell approach, since the performance of the latter is degraded by the interference-limited access link. Specifically, at SNR $= 30$ dB and with single-antenna RRHs and UEs, the DCF scheme shows performance gains of 24.3% and 70.3% for $n_B = N_R = N_U = 3$ and 6, respectively, which implies that the joint processing across the RRHs becomes more important with a larger network size. We also note that the advantages of the cooperative scheme discussed in Section IV-C are more pronounced when the RRHs are equipped with a single antenna rather than multiple antennas.

In Fig. 2, we plot the average sum-rate versus the number n_B of BBU antennas for a C-RAN downlink with $N_R = N_U = 3$, $n_{R,i} = n_{U,k} = 1$ and $P_B = P_{R,i}$. The performance gains of the DCF-based cooperative scheme increase with n_B, since the fronthaul links, that enable joint processing across the RRHs, become more reliable. Furthermore, we observe that the cooperative scheme with a separate design of the fronthaul and access links shows performance close to that of the joint design when the fronthaul links are sufficiently reliable.

VI. Conclusion

We have studied a joint design of fronthaul and radio access links for a C-RAN with wireless fronthaul links. We tackled the weighted sum-rate maximization problem under the assumptions of DF-based single-cell processing and DCF-based cooperative scheme. Via numerical results, it was confirmed that the cooperative scheme significantly outperforms the single-cell approach. Among open problems, we mention here robust and intercluster designs of the DCF-based scheme in the presence of imperfect channel state information and intercluster interference, and an improved DF-based approach which allows multiple RRHs to cooperate to serve same UEs.

[3]It was observed from our simulation that the presence of channel estimation error or OCI signals reduces the performance gain of the proposed DCF-based scheme, but it still outperforms the DF-based single-cell scheme.

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