Interference Mitigation via Rate-Splitting in Cloud Radio Access Networks

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***Abstract*—Cloud-radio access networks (C-RAN) help overcoming the scarcity of radio resources by enabling dense deployment of base-stations (BSs), and connecting them to a central-processor (CP). This paper considers the downlink of a C-RAN, and evaluates rate-splitting (RS) and common-message decoding techniques, as a means to enable large-scale interference management. To this end, the paper proposes splitting the message of each user at the CP into a private part decodable at one user, and a common part decodable at a subset of users for the sole purpose of interference mitigation. The paper then focuses on maximizing the weighted sum-rate subject to backhaul capacity and transmission power constraints, so as to determine the RS mode of each user, and the associated beamforming vectors. The paper proposes solving such a complicated non-convex optimization problem using an inner-convex approximation approach, which guarantees achieving a stationary solution to the problem. Numerical results show that the proposed method provides significant gain compared to classical interference mitigation techniques that do not rely on RS and common message decoding.**

I. Introduction

The fifth-generation (5G) of wireless networks is expected to address the requirements for higher data-rates and for connecting a massive number of devices to the network. Due to scarcity of radio frequency resources, dense deployment of base-stations (BSs) is thought to be an important tool to realize this 5G vision. With spatial-reuse of dense small cells, the distance between BSs and users is reduced, thus enhancing the quality of the received signal. However, this paradigm shift towards a large number of BSs and connected devices makes inter-cell interference a limiting factor against achieving high spectral efficiency. In this context, C-RAN is a promising architecture that enables this paradigm shift while enabling sophisticated inter-cell interference management techniques. This motivates the work in this paper.

In C-RAN, a number of BSs is connected to a central processor (CP) at the cloud via capacity-limited backhaul links. Such connectivity allows the CP to mitigate inter-cell interference by establishing cooperation between BSs using central encoding of the users' messages and joint design of the beamformers. In the extreme of infinite backhaul capacity, the C-RAN boils down to a broadcast channel (BC). In the opposite extreme of zero backhaul capacity, the C-RAN becomes similar to an interference channel (IC). Thus it is interesting to bridge the BC–IC extremes at finite backhaul capacity by exploiting the CP capabilities. With this in mind, this paper proposes a C-RAN interference mitigation technique wherein rate-splitting (RS) and joint beamforming design are performed at the CP. In RS, a user's message is split into a private part decodable at one user, and a common part decodable at a subset of users. Common message decoding by an unintended user helps in reducing its interference, which is further reduced by joint beamforming design. The C-RAN architecture offers a natural platform for such RS and beamforming techniques, and further enables each user to be simultaneously served by several BSs.

In the seminal work [1], it was shown that such a RS technique leads to the largest known achievable rate-region in a 2-user IC. RS was later shown in [2] to achieve rates within one-bit from the capacity of the 2-user IC. Inspired by these information-theoretical studies, the authors in [3] generalized this RS scheme to a practical multicell-network showing significant improvement in the achievable rate induced by RS. Since then, RS has gained a lot of attention. Recently, the authors of [4] studied RS in non-orthogonal unicast and multicast transmission based on Layered Division Multiplexing (LDM), showing the gain of RS in these scenarios. The authors in [5] proposed a novel RS based multiple access scheme which generalizes and outperforms conventional interference mitigation techniques in multiple access systems such as Space-Division Multiple Access (SDMA) and Non-Orthogonal Multiple Access (NOMA).

In the context of C-RAN adopted in the current paper, however, the performance is not only limited by interference level, but also by the finite capacity of backhaul links. The authors in [6] considered a C-RAN downlink system with limited backhaul capacity, and proposed a framework for joint design of beamformers and serving BSs clusters at the CP. However, [6] did not incorporate RS and common message decoding. Thus, it remains interesting to discover the gains of RS in a C-RAN with limited backhaul capacity.

In this work, we propose using RS and common messages decoding in downlink C-RANs, and explore their benefit for large-scale interference management. We formulate a weighted

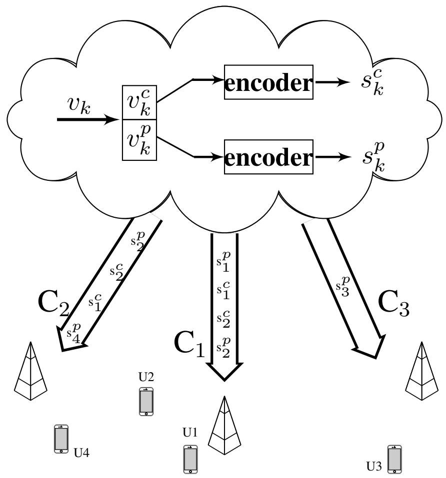

Fig. 1: A C-RAN system with three cells. Both private and common messages are designed at the cloud.

sum-rate (WSR) maximization problem subject to backhaul capacity and per-base-station transmit power constraints, so as to determine the RS splitting mode of each user, and the beamforming vectors associated with the private and common message parts. We show that this problem is generally NP-hard. Then, we propose a polynomial time algorithm to find a stationary solution, and demonstrate the quality of this solution through numerical simulations. Consequently, we show the benefits of the proposed scheme in improving the achievable rate compared to the state-of-the art, in both the backhaul-limited and interference-limited regimes.

II. System Model

We consider a C-RAN system consisting of a set of multi-antenna BSs $\mathcal{N} = \{1, 2, \ldots, N\}$, serving a set of single-antenna users $\mathcal{K} = \{1, 2, \ldots, K\}$ (Fig. 1). Each BS is equipped with $L > 1$ antennas. The BSs are connected to a CP located in the cloud via backhaul links with capacity $C_n, n \in \mathcal{N}$. In this system, user k requests a message v_k of rate R_k. The requested messages are jointly encoded at the CP into signals s_k. The CP then shares combinations of s_k (or parts thereof) with the BSs through the backhaul links. This data-sharing is possible if the rate of signals shared with BS n does not exceed the backhaul capacity C_n. This will be made more explicit when we describe RS.

Upon receiving these signals, BS n constructs $\mathbf{x}_n \in \mathbb{C}^{L\times 1}$, $n \in \mathcal{N}$, subject to a transmit power constraint $\mathbb{E}\left\{\mathbf{x}_n^H \mathbf{x}_n\right\} \leq P_n^{\text{Max}} \quad \forall n \in \mathcal{N}$, where P_n^{Max} is the maximum transmit power available at BS n. Then, BS n sends $\mathbf{x}_n$.

Let $\mathbf{h}_{n,k} \in \mathbb{C}^{L\times 1}$ denote the channel vector between BS n and user k, and $\mathbf{h}_k = \left[\mathbf{h}_{1,k}^T, \mathbf{h}_{2,k}^T, ..., \mathbf{h}_{N,k}^T\right]^T \in \mathbb{C}^{NL\times 1}$ be the aggregate channel vector of user k. We can write the received signal at user k as

$$y_k = \mathbf{h}_k^H \mathbf{x} + n_k \tag{1}$$

where, $n_k \sim \mathcal{CN}\left(0, \sigma^2\right)$ is the additive white Gaussian noise (AWGN), and $\mathbf{x} = [\mathbf{x}_1^T, \ldots, \mathbf{x}_N^T]^T$.

We assume that the CP has complete knowledge of the instantaneous channel state information (CSI) of all BSs. We adopt a block-based transmission model where each transmission block consists of several time slots. The channel fading coefficients remain constant within one block and may vary independently from one block to another.

III. Transmission Scheme and Achievable Rate

The proposed transmission scheme consists of RS, joint beamforming, and successive common message decoding. We start by describing RS.

A. Rate Splitting

The CP first splits v_k into a private message v_k^p and a common message v_k^c. Afterwards, the CP encodes the private and common messages into s_k^p and s_k^c, respectively, as illustrated in Fig. 1. We shall denote the corresponding rates as R_k^p and R_k^c, respectively. Hence, $R_k = R_k^p + R_k^c$.

B. Beamforming, Signal Construction, and Data-Sharing

In a C-RAN, a BS can serve multiple users simultaneously. Thus the CP has to combine signals of multiple users and send them to BSs. Let $\mathcal{K}_n^p, \mathcal{K}_n^c \subseteq \mathcal{K}$ be the subset of users served by BS n with a private or common message, respectively, i.e.,

$$\mathcal{K}_n^p := \left\{k \in \mathcal{K} |\ \text{BS } n \text{ delivers } s_k^p \text{ to user } k\right\}, \tag{2}$$

$$\mathcal{K}_n^c := \left\{k \in \mathcal{K} |\ \text{BS } n \text{ delivers } s_k^c \text{ to user } k\right\}. \tag{3}$$

Moreover, let the beamformers used by BS n to send s_k^p and s_k^c to user k be denoted $\mathbf{w}_{n,k}^p$ and $\mathbf{w}_{n,k}^c$, respectively. Then, the CP sends $s_k^p \in \mathcal{K}_n^p$, $s_k^c \in \mathcal{K}_n^c$ and their beamformers over the backhaul links to BS n, which imposes the constraint

$$\sum_{k\in\mathcal{K}_n^p} R_k^p + \sum_{k\in\mathcal{K}_n^c} R_k^c \leq C_n \quad \forall n \in \mathcal{N} \tag{4}$$

due to the capacity constraint of the backhaul.[1] BS n then constructs $\mathbf{x}_n$ as

$$\mathbf{x}_n = \sum_{k\in\mathcal{K}_n^p} \mathbf{w}_{n,k}^p s_k^p + \sum_{k\in\mathcal{K}_n^c} \mathbf{w}_{n,k}^c s_k^c. \tag{5}$$

C. Successive Decoding

At this step, the received signal at user k can be written as

$$y_k = \mathbf{h}_k^H \left(\mathbf{w}_k^p s_k^p + \mathbf{w}_k^c s_k^c\right) + \sum_{j\in\mathcal{K}\setminus k} \mathbf{h}_k^H \left(\mathbf{w}_j^p s_j^p + \mathbf{w}_j^c s_j^c\right) + n_k,$$

where $\mathbf{w}_k^p = [(\mathbf{w}_{1,k}^p)^T, ..., (\mathbf{w}_{N,k}^p)^T]^T$ is the aggregate beamforming vector associated with the private message of user k, and $\mathbf{w}_k^c$ is defined similarly for the common message.

The main purpose of using common messages is to mitigate interference in the network. Decoding a strong interferer's common messages can significantly improve a user's achievable rate. From this perspective, the order in which user k

[1] We ignore the overhead due to sending the beamformers since these need to be sent only when CSI changes.

decodes the intended messages plays an important role in determining the achievable rate. Although joint decoding of all common and private messages at user k would result in higher rates, its implementation is complicated in practice, in particular when the network and the intended set of messages to be decoded by each user is large. Therefore, in this paper, we focus on a successive decoding strategy, wherein user k decodes a subset of all common messages in a fixed decoding order as described next.

Let $z_{n,k}$ be the strength of the transmit signal of BS n at user k, and define the set of interferer BSs of user k as:

$$\mathcal{N}_k := \left\{ n \in \mathcal{N} | \max_{m \in \mathcal{N}} z_{m,k} - z_{n,k} \leq \mu \right\}, \tag{6}$$

for some $\mu > 0$. Moreover, let $\mathcal{M}_k$ denote set of users who shall decode s_k^c, i.e.,

$$\mathcal{M}_k := \{ j \in \mathcal{K} | \text{ user } j \text{ decodes } s_k^c \}. \tag{7}$$

User k chooses to decode the common message of users who have strongest channels to the BSs in $\mathcal{N}_k$. The set of common messages that user k shall decode is denoted

$$\Phi_k := \{ j \in \mathcal{K} | \ k \in \mathcal{M}_j \}, \tag{8}$$

and is computed as outlined in Algorithm 1. The decoding order at user k is dictated by the following set function

$$\pi_k(j) : \Phi_k \to \{1, 2, \ldots, |\Phi_k|\}.$$

Now we can write $\mathbf{y}_k$, the received signal at user k, as follows,

$$y_k = \underbrace{\left(\mathbf{h}_k^H \mathbf{w}_k^p s_k^p + \sum_{j \in \Phi_k} \mathbf{h}_k^H \mathbf{w}_j^c s_j^c \right)}_{\text{Signal intended to be decoded}} + \underbrace{\sum_{j \in \mathcal{K} \setminus k} \mathbf{h}_k^H \mathbf{w}_j^p s_j^p + \sum_{l \in \mathcal{K} \setminus \Phi_k} \mathbf{h}_k^H \mathbf{w}_l^c s_l^c + n_k}_{\text{Interference plus noise signal}}. \tag{9}$$

Algorithm 1 Determining the set $\Phi_k, \ \forall k \in \mathcal{K}$ and clusters $\mathcal{K}_n^c, \ \forall n \in \mathcal{N}$.

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1. $\Phi_k \leftarrow \varnothing \ \forall k \in \bigcup_{n \in \mathcal{N}} \mathcal{K}_n^p$
2. $\mathcal{K}_n^c \leftarrow \varnothing \ \forall n \in \mathcal{N}$, $\mathcal{K}^{\text{total}} \leftarrow \bigcup_{n \in \mathcal{N}} \mathcal{K}_n^p$
3. Initialize $\mathcal{N}_k \leftarrow$ as in (6)
4. **for** $k \in \mathcal{K}^{\text{total}}$ **do**.
5.   **while** $\mathcal{K}^{\text{total}} \neq \varnothing$ and $\mathcal{N}_k \neq \varnothing$ **do**
6. $n^* \leftarrow \underset{n \in \mathcal{N}}{\text{argmax}} \|\mathbf{h}_{n,k}\|^2$, $k^* \leftarrow \underset{k \in \mathcal{K}_{n^*}^p}{\text{argmax}} \|\mathbf{h}_{n^*,k}\|^2$
7. $\Phi_k \leftarrow \Phi_k \cup \{k^*\}$, $\mathcal{K}_n^c \leftarrow \mathcal{K}_n^c \cup \{k^*\}$,
8. $\mathcal{N}_k \leftarrow \mathcal{N}_k \setminus \{n^*\}$
9.   **end while**
10. **end for**

D. Achievable Rate

Let $\Gamma_k^p, \Gamma_{k,i}^c$ denote the signal to interference plus noise ratios (SINR's) of user k, when decoding its private message and the common message of user i respectively. Based on equation (9) we can write,

$$\Gamma_k^p = \frac{\left| \mathbf{h}_k^H \mathbf{w}_k^p \right|^2}{\sum\limits_{j \in \mathcal{K} \setminus k} \left| \mathbf{h}_k^H \mathbf{w}_j^p \right|^2 + \sum\limits_{l \in \mathcal{K} \setminus \Phi_k} \left| \mathbf{h}_k^H \mathbf{w}_l^c \right|^2 + \sigma^2} \tag{10}$$

$$\Gamma_{k,i}^c = \frac{\left| \mathbf{h}_k^H \mathbf{w}_i^c \right|^2}{T_k + \sum\limits_{l \in \mathcal{K} \setminus \Phi_k} \left| \mathbf{h}_k^H \mathbf{w}_l^c \right|^2 + \sum\limits_{\substack{m \in \Phi_k \\ \pi_k(m) > \pi_k(i)}} \left| \mathbf{h}_k^H \mathbf{w}_m^c \right|^2} \tag{11}$$

where $T_k = \sum_{j \in \mathcal{K}} \left| \mathbf{h}_k^H \mathbf{w}_j^p \right|^2 + \sigma^2$, and where we assumed that each user always decodes their private message last.

Let B be the transmission bandwidth. The total achievable rate of user k is then $R_k = R_k^p + R_k^c$, which satisfies the following achievability conditions:

$$\Gamma_k^p \geq 2^{R_k^p / B} - 1 \quad \forall k \in \mathcal{K}, \tag{12}$$

$$\Gamma_{i,k}^c \geq 2^{R_k^c / B} - 1 \quad \forall i \in \mathcal{M}_k \text{ and } \forall k \in \mathcal{K}. \tag{13}$$

IV. Problem Formulation and Proposed Solution

A. Weighted Sum-Rate Maximization

The paper considers the problem of maximizing the weighted sum-rate (WSR), so as to determine the common and private beamformers of each user. The WSR maximization considered can be written as:

$$\underset{\left\{ \mathbf{w}_k^p, \mathbf{w}_k^c | \forall k \in \mathcal{K} \right\}}{\text{maximize}} \quad \sum_{k=1}^{K} \alpha_k \left(R_k^p + R_k^c \right) \tag{14a}$$

$$\text{subject to} \quad (4), (12), (13) \tag{14b}$$

$$\sum_{k \in \mathcal{K}_n^p} \left\| \mathbf{w}_{n,k}^p \right\|_2^2 + \sum_{k \in \mathcal{K}_n^c} \left\| \mathbf{w}_{n,k}^c \right\|_2^2 \leq P_n^{\text{Max}} \quad \forall n \in \mathcal{N}. \tag{14c}$$

We will study this problem for fixed $\mathcal{K}_n^c$, $\mathcal{K}_n^p$, $\mathcal{M}_k$, as well as decoding order π_k. Since we assume a block-fading model where the channel coefficients vary slowly, there is no need to update these sets and decoding order very often. Despite the above assumptions, problem (14) remains challenging to solve, because of the non-convexity of the objective function (14a) and the constraints (12) and (13). To tackle this challenge, we present a practical approach to solve problem (14). The proposed approach guarantees achieving a stationary solution to the problem, and provides a decent performance improvement as compared to the classical scheme based on private-information transmission only, as shown later in Sec. V.

B. Proposed Solution

A key observation leading to our proposed solution is to note that the problem (14) is equivalent to the multi-group multicasting beamforming problem in terms of optimization of transmit beamformers. To see this equivalence, we note that the set $\mathcal{M}_k$ represents a multicasting group where the message s_k^c is to be decoded by all users $j \in \mathcal{M}_k$. The difference here is that the common-message is desired only at the intended receiver, while other users can decode it for mitigating interference. In [7], [8], it was shown that a simplified instance of this problem in which a single BS is serving multiple multicasting groups was proved to be an NP-hard problem. The authors in [7] applied an inner convex approximation approach to maximize the minimum SINR subject to power constraints.

Due to this similarity, we adopt a similar approach and extend it to solve (14). First, we write (14) in an equivalent formulation. Then, we apply inner convex approximation to obtain a stationary solution.

1) Iterative Algorithm for Solving (14)*:* With help of additional variables $t_k^p, \beta_k \forall k \in \mathcal{K}$ and $t_k^c, \beta_{i,k} \forall k \in \mathcal{K}$ and $\forall i \in \mathcal{M}_k$, problem (14) can be equivalently expressed as follows

$$\underset{\left\{\mathbf{w}_k^p, \mathbf{w}_k^c, |\forall k \in \mathcal{K}\right\}, \mathbf{t}, \boldsymbol{\beta}}{\text{maximize}} \quad \sum_{k=1}^{K} \alpha_k \left(t_k^p + t_k^c\right)$$

$$\text{subject to} \quad (14c) \tag{15a}$$

$$\sum_{\left\{k \mid n \in \mathcal{N}_k^p\right\}} t_k^p + \sum_{\left\{k \mid n \in \mathcal{N}_k^c\right\}} t_k^c \leq C_n \quad \forall n \in \mathcal{N} \tag{15b}$$

$$g_{1,k}\left(t_k^p, \beta_k^p, \mathbf{w}_k^p\right) \leq 0 \tag{15c}$$

$$g_{2,i,k}\left(t_k^c, \beta_{i,k}^c, \mathbf{w}_k^c\right) \leq 0 \tag{15d}$$

$$g_{3,k}\left(\beta_k^p, \mathbf{w}_k^p\right) \leq 0 \tag{15e}$$

$$g_{4,i,k}\left(\beta_{i,k}^c, \mathbf{w}_k^c\right) \leq 0 \tag{15f}$$

$$\beta_k^p \leq \beta_k^{\text{Max}} \tag{15g}$$

$$\beta_{i,k}^c \leq \beta_i^{\text{Max}} \quad \forall k \in \mathcal{K}, i \in \mathcal{M}_k. \tag{15h}$$

Here,

$$g_{1,k}\left(t_k^p, \beta_k^p, \mathbf{w}_k^p\right) = \left(2^{t_k^p/B} - 1\right)\beta_k^p - \left|\mathbf{h}_k^H \mathbf{w}_k^p\right|^2 \tag{16}$$

$$g_{2,i,k}\left(t_k^c, \beta_{i,k}^c, \mathbf{w}_k^c\right) = \left(2^{t_k^c/B} - 1\right)\beta_{i,k}^c - \left|\mathbf{h}_i^H \mathbf{w}_k^c\right|^2 \tag{17}$$

$$g_{3,k}\left(\beta_k^p, \mathbf{w}_k\right) = \sum_{j \in \mathcal{K} \setminus k} \left|\mathbf{h}_k^H \mathbf{w}_j^p\right|^2 + \sum_{l \notin \Phi_k} \left|\mathbf{h}_k^H \mathbf{w}_l^c\right|^2 + \sigma^2 - \beta_k^p \tag{18}$$

$$g_{4,i,k}\left(\beta_{i,k}^c, \mathbf{w}_k\right) = T_k + \sum_{l \notin \Phi_k} \left|\mathbf{h}_k^H \mathbf{w}_l^c\right|^2 + \sum_{\substack{m \in \Phi_k \\ \pi_k(m) > \pi_k(i)}} \left|\mathbf{h}_k^H \mathbf{w}_m^c\right|^2 - \beta_{i,k}^c, \tag{19}$$

where $\mathbf{w}_k = [(\mathbf{w}_k^p)^T, (\mathbf{w}_k^c)^T]^T$. Problem (15) is still non-convex due to (15c) and (15d). The first step in our approach is to upper bound the non-convex functions $g_{1,k}$ and $g_{2,k}$ by convex upper-bounds. Note that the function $g_{1,k}\left(t_k^p, \beta_k^p, \mathbf{w}_k^p\right) = g_{1,k}^1\left(t_k^p, \beta_k^p\right) + g_{1,k}^2\left(\mathbf{w}_k^p\right)$ is a sum of two functions, the first part is a multiplication of a convex and linear functions, while the second part is a concave function in the beamformer $\mathbf{w}_k^p$. Let $\tilde{g}_{1,k}\left(t_k^p, \beta_k^p, \mathbf{w}_k^p, \mathbf{Z}^p\right) = \tilde{g}_{1,k}^1\left(t_k^p, \beta_k^p, \tilde{t}_k^p, \tilde{\beta}_k^p\right) + \tilde{g}_{1,k}^2\left(\mathbf{w}_k^p, \widetilde{\mathbf{w}}_k^p\right)$, where

$$\tilde{g}_{1,k}^1\left(t_k^p, \beta_k^p, \tilde{t}_k^p, \tilde{\beta}_k^p\right) = \frac{1}{2}\left(\frac{\tilde{\beta}_k^p}{2^{\frac{\tilde{t}_k^p}{B}}} 2^{2\frac{t_k^p}{B}} + \frac{2^{\frac{\tilde{t}_k^p}{B}}}{\tilde{\beta}_k^p}\left(\beta_k^p\right)^2\right) - \beta_k^p$$

$$\tilde{g}_{1,k}^2\left(\mathbf{w}_k^p, \widetilde{\mathbf{w}}_k^p\right) = -\left|\mathbf{h}_k^H \widetilde{\mathbf{w}}_k^p\right|^2 - 2\Re\left\{\left(\mathbf{h}_k^H \mathbf{h}_k \widetilde{\mathbf{w}}_k^p\right)^H \left(\mathbf{w}_k^p - \widetilde{\mathbf{w}}_k^p\right)\right\}$$

are both convex, and $\mathbf{Z}^p$ is a vector stacking all constants $\tilde{t}_k^p, \tilde{\beta}_k^p, \widetilde{\mathbf{w}}_k^p \quad \forall k \in \mathcal{K}$. In a similar way, define $\tilde{g}_{2,i,k}\left(t_k^c, \beta_{i,k}^p, \mathbf{w}_k^c, \mathbf{Z}^c\right) = \tilde{g}_{2,i,k}^1\left(t_k^c, \beta_{i,k}^c, \tilde{t}_k^c, \tilde{\beta}_{i,k}^c\right) + \tilde{g}_{2,i,k}^2\left(\mathbf{w}_k^c, \widetilde{\mathbf{w}}_k^c\right)$ where

$$\tilde{g}_{2,i,k}^1\left(t_k^c, \beta_{i,k}^c, \tilde{t}_k^c, \tilde{\beta}_{i,k}^c\right) = \frac{\tilde{\beta}_{i,k}^c}{2^{\frac{\tilde{t}_k^c}{B}}} 2^{2\frac{t_k^c}{B} - 1} + \frac{\left(\beta_{i,k}^c\right)^2}{\tilde{\beta}_{i,k}^c} 2^{\frac{\tilde{t}_k^c}{B} - 1} - \beta_{i,k}^c$$

$$\tilde{g}_{2,i,k}^2\left(\mathbf{w}_k^c, \widetilde{\mathbf{w}}_k^c\right) = -\left|\mathbf{h}_i^H \widetilde{\mathbf{w}}_k^c\right|^2 - 2\Re\left\{\left(\mathbf{h}_i^H \mathbf{h}_i \widetilde{\mathbf{w}}_k^c\right)^H \left(\mathbf{w}_k^c - \widetilde{\mathbf{w}}_k^c\right)\right\},$$

where $\mathbf{Z}^c$ is a vector stacking all constants $\tilde{t}_k^c, \tilde{\beta}_{i,k}^c, \widetilde{\mathbf{w}}_k^c \quad \forall k \in \mathcal{K}, i \in \mathcal{M}_k$. Then we have the following statement.

Lemma 1. For all feasible points $\mathbf{Z}^p \in \mathcal{C}^p$ and $\mathbf{Z}^c \in \mathcal{C}^c$ where $\mathcal{C}^p$ is the feasible set defined by constraints (15b), (15c), (15e) and (15g), and $\mathcal{C}^c$ is the feasible set defined by constraints (15b), (15d), (15f) and (15h), we have

$$\tilde{g}_{1,k}\left(t_k^p, \beta_k^p, \mathbf{w}_k^p, \mathbf{Z}^p\right) \geq g_{1,k}\left(t_k^p, \beta_k^p, \mathbf{w}_k^p\right) \tag{20}$$

$$\tilde{g}_{2,i,k}\left(t_k^c, \beta_{i,k}^p, \mathbf{w}_k^c, \mathbf{Z}^c\right) \geq g_{2,i,k}\left(t_k^c, \beta_{i,k}^p, \mathbf{w}_k^c\right). \tag{21}$$

2) Inner Convex Approximations: Based on (20) and (21) we apply inner convex approximations to (15). Iteratively, we solve the following:

$$\underset{\left\{\mathbf{w}_k^p, \mathbf{w}_k^c, |\forall k \in \mathcal{K}\right\}, \mathbf{t}, \boldsymbol{\beta}}{\text{maximize}} \quad \sum_{k=1}^{K} \alpha_k \left(t_k^p + t_k^c\right)$$

$$\text{subject to} \quad (15a) - (15b) \text{ and } (15e) - (15h) \tag{22a}$$

$$\tilde{g}_{1,k}\left(t_k^p, \beta_k^p, \mathbf{w}_k^p, \mathbf{Z}_u^p\right) \leq 0 \tag{22b}$$

$$\tilde{g}_{2,i,k}\left(t_k^c, \beta_{i,k}^p, \mathbf{w}_k^c, \mathbf{Z}_u^c\right) \leq 0 \tag{22c}$$

where u is the iteration number and $\mathbf{Z}_u^p, \mathbf{Z}_u^c$ are computed in the previous iteration. Let $\widehat{\mathbf{Z}}_u = [(\mathbf{Z}_u^p)^T, (\mathbf{Z}_u^c)^T]^T$. Algorithm 2 outlines the proposed algorithm based on the inner convex approximation of (20) and (21).

Algorithm 2 Inner convex approximation of (15).

1: $u \leftarrow 0$, $\mathbf{Z}_0 \leftarrow \widehat{\mathbf{Z}}_0$, where $\widehat{\mathbf{Z}}_0 \in \mathcal{C}^p \cup \mathcal{C}^c$
2: **while** $\mathbf{Z}_u$ not a stationary solution of (15) **do**
3: Solve the convex problem (22) and compute $\mathbf{Z}_u^p, \mathbf{Z}_u^c$
4: $\mathbf{Z}_{u+1} \leftarrow \mathbf{Z}_u + \gamma_u \left(\widehat{\mathbf{Z}}_{u+1} - \mathbf{Z}_u\right)$ for some $\gamma \in (0, 1]$
5: $u \leftarrow u + 1$
6: **end while**

TABLE I: The percentage gain achieved by using rate splitting.

Backhaul Capacity	Dense Network	Normal Network
100 Mbps	6.58 %	1.34 %
200 Mbps	12.84 %	9.09 %
300 Mbps	19.18 %	9.38 %
450 Mbps	20.31 %	9.59 %

V. Numerical Results

In this section, we perform numerical simulations to show the benefits of RS in C-RAN systems. We consider a conventional 7-cell wrapped-around network where $C_1 = C_2 = \cdots = C_N$. The simulation parameters are the same as those in [6, Table I]. We assume the distance between cells is 0.8 km and 0.2 km, which we refer to as a "normal network" and a "dense network", respectively.

We generate one user/cell uniformly at random, and we compare our scheme with another interference-mitigation scheme from [6] which uses private-message only (baseline). The percentage gain of our scheme is shown in Table I for various values of backhaul capacities. The achievable sum-rate versus the backhaul capacity is shown in Fig. 2. We can see that our scheme provides significant gain especially in the dense network scenario, which highlights the role of RS as an interference mitigation technique. The gain increases as the backhaul capacity increases, up to a certain value where the gain nearly saturates. This marks the boundary between the backhaul-limited regime and the interference-limited regime.

Fig. 3 shows a similar comparison for a network with 4 users/cell. We notice that when the backhaul capacity value is 100 Mbps, both schemes achieve almost the same sum-rate. This is because in this case the network is backhaul-limited where the major performance limitation due to the backhaul capacity and not to interference. However, as we move towards higher backhaul capacities, we note that our scheme outperforms the baseline and approaches the total backhaul capacity ($7\times$ backhaul capacity) as opposed to the baseline in a dense network scenario. The gain in the 1 user/cell case is higher than the 4 user/cell case because we assume fixed private and common clusters when we compute the optimal beamformers. We actually use private clusters which are optimized for the baseline scheme. Since the clustering effect is more dominant when the number of users is higher, the gain decreases. We plan to enhance this scheme in the future by developing better approaches for private and common clustering.

We note that Algorithm 2 converges generally fast. Simulations showed that the objective function of (22) increases monotonically with each iteration and converges after a finite number (< 30) of iterations to a stationary point. The proof of achieving a stationary point is omitted due to lack of space.

VI. Conclusions

This paper amalgamates the benefits of RS in C-RAN for enabling large-scale interference management. It solves the problem of maximizing the weighted sum-rate subject to finite backhaul capacity and transmission power constraints. Simulations show that the RS scheme outperforms the conventional private-information transmission approach. The gain is more significant in dense networks as well as interference limited regimes.

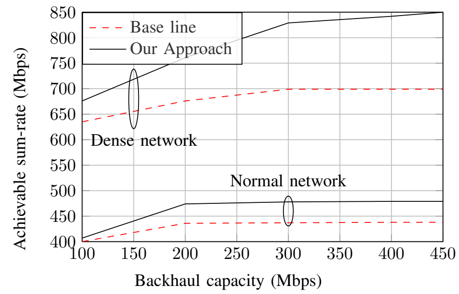

Fig. 2: Sum-rate vs backhaul capacity with 1 user/cell.

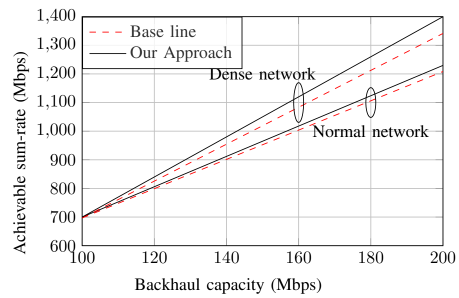

Fig. 3: Sum-rate vs backhaul capacity with 4 users/cell.

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