Joint Designs of Fronthaul Compression and Precoding for Full-Duplex Cloud Radio Access Networks

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***Abstract*—This letter studies a joint design of fronthaul compression and precoding for full-duplex (FD) cloud radio access networks (C-RAN). In this system, each radio unit (RU) takes the role of FD transmission and a control unit connected to all of the RUs via finite-capacity links performs co-operative interference management by centralized baseband processing. There exists non-negligible self-interference (SI) due to FD transmission even after analog SI cancellation (SIC) is applied at the RU. To efficiently alleviate the residual SI, we propose the implementation of additional digital SIC at each RU, which mitigates the SI in baseband and thus reduces the burden of the finite uplink fronthaul capacity. We then consider the problem of maximizing the sum rate of uplink and downlink users while satisfying the per-RU fronthaul capacity and power constraints. The problem is solved by the majorization minimization approach under a difference of convex structure. Through simulation results, we confirm that the proposed FD C-RAN system with SIC implemented at the RUs can achieve substantial gains compared to conventional schemes.**

***Index Terms*—Cloud radio access networks, full-duplex, precoding.**

I. Introduction

CLOUD radio access networks (C-RAN) have recently been regarded as a promising architecture for 5G wireless systems. In specific, C-RAN provides cooperative interference management at a control unit (CU) by separating baseband processing from radio units (RU). The separation is realized by transferring the quantized baseband signals on low-latency fronthaul links between a cluster of RUs and the CU [1]. Since the fronahaul links typically have finite capacity [1], it is important to carefully design precoding and fronthaul compression strategies to achieve high spectral efficiency [2].

In the meantime, full-duplex (FD) systems have also attracted a great amount of attentions due to its potential for providing approximately doubled spectral efficiency over the half-duplex (HD) ones [3], [4]. A key drawback of the FD systems, however, is the presence of self-interference (SI) caused by its own transmission. There have been recent breakthroughs for SI cancellation (SIC) techniques in both analog and digital domain [3]. SIC methods are different in a way that analog SIC uses additional RF chains to cancel the SI, while the digital SIC mitigates the SI in baseband [3].

In [4], FD systems which employ the SIC methods with multi-antenna terminals were extensively studied in a single small-cell scenario. Under the assumption of perfect SIC, [5] studied FD C-RAN systems as a means to cope with uplink-to-downlink (U2D) and downlink-to-uplink (D2U) inter-cell interference. Although [5] offers an information theoretic analysis on significant potential gains of the FD C-RAN system, it does not provide insights on how to design precoding and fronthaul compression.

In this letter, we consider an FD C-RAN where each RU takes a role of FD transmission in case of imperfect SIC and a CU performs cooperative interference management by the centralized baseband processing. Unlike [5], it should be noted that the SIC in analog domain still leaves residual SI in practice due to hardware limitation. Hence, an implementation of additional digital-domain SIC at each RU is proposed in order to alleviate the adverse effect of SI and the finite uplink fronthaul capacity, which is the bottle-neck of the FD C-RAN system. In this case, the RU-related baseband processing is generally less complicated than CoMP joint processing [6], [7] in the sense that while the latter should be implemented at a CU with full centralization [8], the former can be implemented with partial centralization [8].

We then formulate a problem of jointly optimizing the precoding and fronthaul compression to maximize the sum rate of uplink and downlink users while satisfying the per-RU fronthaul capacity and power constraint. Since there exist the combination of D2U and U2D interference, the problem is non-convex in general. Therefore, we solve the problem by the majorization minimization (MM) approach, which transforms a difference-of-convex (DC) problem into a sequence of approximated convex problems with a change of variable and rank-relaxation. From numerical results, we confirm that the proposed FD C-RAN system with SIC implemented at RUs can achieve substantial gains compared to conventional schemes.

Notation: We adopt uppercase boldface letters for matrices and lowercase boldface for vectors. The superscripts $(\cdot)^{\mathsf{T}}$ and $(\cdot)^{\dagger}$ stand for transpose and Hermitian transpose of a matrix or vector, respectively. $|\mathbf{A}|$ refers to the determinant of matrix $\mathbf{A}$. $\mathbf{I}_N$ denotes the identity matrix of size $N \times N$ and $\mathbf{0}_{N\times M}$ refers to the zero matrix of size $N \times M$.

II. System Model

In this letter, we consider an FD C-RAN system where a CU is connected to K_R RUs through wired fronthaul links of finite capacity. In our model, we deploy multi-antenna RUs operating in a FD mode where the transmission and the reception of signals occur at the same time and frequency to support K_D downlink and K_U uplink user equipments (UEs). We assume that each RU has $N_{R,D}$ and $N_{R,U}$ antennas for the transmission and the reception, respectively, and thus, $N_{B,D} = K_R N_{R,D}$ transmit and $N_{B,U} = K_R N_{R,U}$ receive antennas are employed at the RUs. All uplink UEs are equipped with N_U transmit antennas, and all downlink UEs have N_D receive antennas. Throughout this letter, we denote the sets of

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the uplink UEs, the downlink UEs and the RUs by $\mathcal{K}_U$, $\mathcal{K}_D$ and $\mathcal{K}_R$, respectively.

A. Downlink System Model

At the CU, the message signal $M_{D,k}$ for the k-th downlink UE is encoded to produce the data symbol $\mathbf{s}_{D,k} \in \mathbb{C}^{L_{D,k}\times 1}$ distributed as $\mathcal{CN}(\mathbf{0},\mathbf{I})$ for all k, where $L_{D,k}$ represents the number of data streams for the downlink UE k. Then, each encoded baseband signals $\{\mathbf{s}_{D,k}\}_{k\in\mathcal{K}_R}$ is precoded by the precoding matrices $\mathbf{V}_{D,k} \in \mathbb{C}^{N_{B,D}\times L_{D,k}}$ to compute the transmitted signal vector $\tilde{\mathbf{x}}_D \in \mathbb{C}^{N_{B,D}\times 1}$ as $\tilde{\mathbf{x}}_D = \sum_{k\in\mathcal{K}_D}\mathbf{V}_{D,k}\mathbf{s}_{D,k} = [\tilde{\mathbf{x}}_{D,1}^T,\ldots,\tilde{\mathbf{x}}_{D,K_R}^T]^T$, where $\tilde{\mathbf{x}}_{D,i} \triangleq \mathbf{E}_i\sum_{k\in\mathcal{K}_D}\mathbf{V}_{D,k}\mathbf{s}_{D,k}$ is the i-th sub-vector of $\tilde{\mathbf{x}}_D$ transferred to the i-th RU with the shaping matrix $\mathbf{E}_i$ defined as

$$\mathbf{E}_i = [\mathbf{0}^{\dagger}_{(i-1)N_{R,D}\times N_{R,D}},\ \mathbf{I}_{N_{R,D}},\ \mathbf{0}^{\dagger}_{(K_R-i)N_{R,D}\times N_{R,D}}]^{\dagger}. \quad (1)$$

Then, the CU generates the compressed bit streams for the precoded baseband signals $\tilde{\mathbf{x}}_{D,i}$ and send them to the RUs.

After receiving the compressed bit streams, each RU i restores them into $\mathbf{x}_{D,i}$, which is a quantized version of $\tilde{\mathbf{x}}_{D,i}$. Assuming a Gaussian test channel as in [1], $\mathbf{x}_{D,i}$ can be modelled as $\mathbf{x}_{D,i} = \tilde{\mathbf{x}}_{D,i}+\mathbf{q}_{D,i}$ with $\mathbf{q}_{D,i} \sim \mathcal{CN}(\mathbf{0},\mathbf{\Omega}_{D,i})$ representing the quantization noise independent of the input signal $\tilde{\mathbf{x}}_{D,i}$. Thus, to meet the i-th downlink fronthaul capacity constraint $C_{D,i},\ i\in\mathcal{K}_R$, the CU should determine the covariance matrices $\mathbf{W}_{D,l} = \mathbf{V}_{D,l}\mathbf{V}_{D,l}^{\dagger}$ of the precoding signals and the quantization noise covariance matrix $\mathbf{\Omega}_{D,i}$ which satisfy the following downlink front-haul rate condition

$$g_{D,i} \triangleq \log\left|\sum_{k\in\mathcal{K}_D}\mathbf{E}_i^{\dagger}\mathbf{W}_{D,k}\mathbf{E}_i + \mathbf{\Omega}_{D,i}\right| - \log\left|\mathbf{\Omega}_{D,i}\right| \le C_{D,i}. \quad (2)$$

Under these precoding and fronthaul compression model, the per-RU power constraint $\mathbb{E}\left\|\mathbf{x}_{D,i}\right\|^2 \le P_{R,i}$ is also given by

$$\mathrm{tr}\Big(\sum_{k\in\mathcal{K}_D}\mathbf{E}_i^{\dagger}\mathbf{W}_{D,k}\mathbf{E}_i + \mathbf{\Omega}_{D,i}\Big) \le P_{R,i},\ \forall i\in\mathcal{K}_R. \quad (3)$$

For the wireless access links between the RUs and downlink UEs, we define $\mathbf{H}_{D,k,i} \in \mathbb{C}^{N_D\times N_{R,D}}$ and $\mathbf{G}_{UE,k,l} \in \mathbb{C}^{N_D\times N_U}$ as the desired channel matrix from the i-th RU to the k-th downlink UE and the interfering channel matrix from the l-th uplink UE to the k-th downlink UE, respectively. When the k-th downlink UE receives $\mathbf{x}_D = [\mathbf{x}_{D,1}^T,\ldots,\mathbf{x}_{D,K_R}^T]^T \in \mathbb{C}^{N_{B,D}\times 1}$ from all RUs through the stacked downlink channel matrix $\mathbf{H}_{D,k} = [\mathbf{H}_{D,k,1},\ldots,\mathbf{H}_{D,k,K_R}] \in \mathbb{C}^{N_D\times N_{B,D}}$, it is interfered by the uplink signal $\mathbf{x}_{U,l}$ from the l-th uplink UE through the interference channel $\mathbf{G}_{\mathrm{UE},k,l}$. Thus, the received signal vector $\mathbf{y}_{D,k} \in \mathbb{C}^{N_D\times 1}$ at the downlink UE k is written by

$$\mathbf{y}_{D,k} = \mathbf{H}_{D,k}\mathbf{x}_D + \sum_{l\in\mathcal{K}_U}\mathbf{G}_{\mathrm{UE},k,l}\mathbf{x}_{U,l} + \mathbf{z}_{D,k} \quad (4)$$

where $\mathbf{z}_{D,k} \sim \mathcal{CN}(\mathbf{0},\sigma_D^2\mathbf{I})$ is the additive noise at UE k.

B. Uplink System Model

For uplink transmissions, the k-th uplink UE first encodes its message $M_{U,k}$ to create the encoded baseband signal $\mathbf{s}_{U,k} \in \mathbb{C}^{L_{U,k}\times 1}$ with $\mathbf{s}_{U,k} \sim \mathcal{CN}(\mathbf{0},\mathbf{I})$ for all $k\in\mathcal{K}_U$. Then, the linear precoding $\mathbf{V}_{U,k} \in \mathbb{C}^{N_U\times L_{U,k}}$ is applied to calculate $\mathbf{x}_{U,k} = \mathbf{V}_{U,k}\mathbf{s}_{U,k}$ with the transmit power constraint $\mathbb{E}\|\mathbf{x}_{U,k}\|^2 \le P_{U,k}$. This can be restated as

$$\mathrm{tr}\Big(\mathbf{W}_{U,k}\Big) \le P_{U,k},\ \forall k\in\mathcal{K}_U, \quad (5)$$

where the covariance matrix is defined as $\mathbf{W}_{U,k} = \mathbf{V}_{U,k}\mathbf{V}_{U,k}^{\dagger}$.

Let us denote $\mathbf{H}_{U,i,k} \in \mathbb{C}^{N_{R,U}\times N_U}$ and $\mathbf{G}_{R,i,j} \in \mathbb{C}^{N_{R,U}\times N_{R,D}}$ as the uplink channel matrix from the k-th uplink UE to the i-th RU and the D2U interference channel matrix from the j-th RU to the i-th RU, respectively. When the i-th RU receives the signal vector $\mathbf{x}_U = [\mathbf{x}_{U,1}^T,\ldots,\mathbf{x}_{U,K_U}^T]^T \in \mathbb{C}^{K_U N_U\times 1}$ transmitted by all the uplink UEs through $\mathbf{H}_{U,i} = [\mathbf{H}_{U,i,1},\ldots,\mathbf{H}_{U,i,K_U}] \in \mathbb{C}^{N_{R,U}\times K_U N_U}$, $\mathbf{x}_{D,j}$ from RU j interferes via the D2U interference channel $\mathbf{G}_{\mathrm{RU},i,j}$. Then, the received signal vector $\mathbf{y}_{U,i} \in \mathbb{C}^{N_{R,U}\times 1}$ at RU i is given by

$$\mathbf{y}_{U,i} = \mathbf{H}_{U,i}\mathbf{x}_U + \sum_{j\in\mathcal{K}_R}\mathbf{G}_{R,i,j}\mathbf{x}_{D,j} + \mathbf{z}_{U,i}, \quad (6)$$

where $\mathbf{z}_{U,i} \sim \mathcal{CN}(\mathbf{0},\sigma_U^2\mathbf{I})$ designates the additive Gaussian noise with variance σ_U^2, and $\mathbf{G}_{R,i,i}$ stands for the residual SI channel after analog SIC at the i-th RU.

Note that in practice, the residual SI signal $\mathbf{G}_{\mathrm{RU},i,i}\mathbf{x}_i$ may still be non-negligible compared to the desired uplink signal $\mathbf{H}_{U,i}\mathbf{x}_U$. Moreover, it is not desirable to send this unnecessarily large interference signal through the capacity-limited fronthaul links. Therefore, each FD RUs need to implement an additional digital SIC operation with simple baseband processing to reliably deliver the desired signal via fronthaul link to the CU.

Denoting $\tilde{\mathbf{G}}_{R,i,i}$ as the effective SI channel for RU i after the digital SIC at RU, the received signals $\bar{\mathbf{y}}_{U,i}$ at RU i is written as

$$\bar{\mathbf{y}}_{U,i} = \sum_{k\in\mathcal{K}_U}\mathbf{H}_{U,i,k}\mathbf{x}_{U,k} + \sum_{j\in\mathcal{K}_R\setminus\{i\}}\mathbf{G}_{R,i,j}\mathbf{x}_{D,j} + \tilde{\mathbf{G}}_{R,i,i}\mathbf{x}_{D,i} + \mathbf{z}_{U,i}. \quad (7)$$

Similar to the downlink compression, the i-th RU then delivers to the CU the compressed digital bit streams $\tilde{\mathbf{y}}_{U,i} = \bar{\mathbf{y}}_{U,i} + \mathbf{q}_{U,i}$, where the quantization noise $\mathbf{q}_{U,i} \sim \mathcal{CN}(\mathbf{0},\mathbf{\Omega}_{U,i})$ is independent of the signal $\bar{\mathbf{y}}_{U,i}$.

By performing decompression of the received bit streams from RU i, the CU reliably recovers the signal vector $\tilde{\mathbf{y}}_{U,i}, \forall i$ as long as the following uplink front-haul rate conditions are satisfied:

$$\tilde{g}_{U,i} \triangleq \log\left|\sum_{k\in\mathcal{K}_U}\mathbf{\Psi}_{U,i,k} + \tilde{\mathbf{\Theta}}_i + \mathbf{\Omega}_{U,i} + \sigma_U^2\mathbf{I}\right| - \log\left|\mathbf{\Omega}_{U,i}\right| \le C_{U,i}, \quad (8)$$

where $\mathbf{\Psi}_{U,i,k} = \mathbf{H}_{U,i,k}\mathbf{W}_{U,k}\mathbf{H}_{U,i,k}^{\dagger}$ stands for the uplink covariance matrix from uplink UE k to RU i, $\tilde{\mathbf{\Theta}}_i = \sum_{j\in\mathcal{K}_R\setminus\{i\}}\mathbf{G}_{R,i,j}\mathbf{\Omega}_{D,j}\mathbf{G}_{R,i,j}^{\dagger} + \tilde{\mathbf{G}}_{R,i,i}\mathbf{\Omega}_{D,i}\tilde{\mathbf{G}}_{R,i,i}^{\dagger} + \sum_{k\in\mathcal{K}_D}\bar{\mathbf{G}}_i\mathbf{W}_{D,k}\bar{\mathbf{G}}_i^{\dagger}$ indicates the D2U interference covariance matrix from all RUs to RU i with $\bar{\mathbf{G}}_i = \sum_{j\in\mathcal{K}_R\setminus\{i\}}\mathbf{G}_{R,i,j}\mathbf{E}_j^{\dagger} + \tilde{\mathbf{G}}_{R,i,i}\mathbf{E}_i^{\dagger}$. It is worth noting that when the digital SIC is performed only at the CU or not provided at all, the SI channel term $\tilde{\mathbf{G}}_{R,i,i}$ in (8) is replaced with $\mathbf{G}_{R,i,i}$. In Section IV, we present some numerical results on how much the implementation of the proposed SIC methods at RUs improves the sum-rate.

Aggregating $\hat{\mathbf{y}}_{U,i}$ for $i\in\mathcal{K}_R$ at the CU, we obtain the stacked uplink signal vector $\hat{\mathbf{y}}_U = [\hat{\mathbf{y}}_{U,1}^T,\ldots,\hat{\mathbf{y}}_{U,\mathcal{K}_R}^T]^T$ as

$$\hat{\mathbf{y}}_U = \sum_{k\in\mathcal{K}_U}\mathbf{H}_{U,k}\mathbf{V}_{U,k}\mathbf{s}_{U,k} + \sum_{j\in\mathcal{K}_R}\tilde{\mathbf{G}}_{R,j}\mathbf{x}_{D,j} + \mathbf{q}_U + \mathbf{z}_U, \quad (9)$$

where $\mathbf{H}_{U,k} = [\mathbf{H}_{U,1,k}^T,\ldots,\mathbf{H}_{U,K_R,k}^T]^T$, $\mathbf{q}_U = [\mathbf{q}_{U,1}^T,\ldots,\mathbf{q}_{U,K_R}^T]^T$, $\tilde{\mathbf{G}}_{R,j} = [\mathbf{G}_{R,1,j}^T,\ldots,\mathbf{G}_{R,j-1,j}^T,\tilde{\mathbf{G}}_{R,j,j}^T,\mathbf{G}_{R,j+1,j}^T,\ldots,\mathbf{G}_{R,K_R,j}^T]^T$, and $\mathbf{z}_U = [\mathbf{z}_{U,1}^T,\ldots,\mathbf{z}_{U,K_R}^T]^T$.

C. Sum Rates of Downlink and Uplink UEs

Similar to [4], the joint optimization of the entire sum-rates of uplink and downlink transmissions gives a useful insight on how much overall performance gain can be achieved compared to HD systems. From (4), the achievable sum rate of downlink

UEs is obtained as

$$R_{\Sigma}^{D}=\sum_{k\in\mathcal{K}_D}\Big(\log\Big|\sum_{l\in\mathcal{K}_D}\boldsymbol{\Psi}_{k,l}^{D}+\boldsymbol{\Phi}_{k}^{D}\Big|-\log\Big|\sum_{l\in\mathcal{K}_D\backslash\{k\}}\boldsymbol{\Psi}_{k,l}^{D}+\boldsymbol{\Phi}_{k}^{D}\Big|\Big), \quad (10)$$

where $\boldsymbol{\Psi}_{k,l}^{D}=\mathbf{H}_{D,k}\mathbf{W}_{D,l}\mathbf{H}_{D,k}^{\dagger}$ and $\boldsymbol{\Phi}_{k}^{D}=\sigma_D^2\mathbf{I}+\mathbf{H}_{D,k}\boldsymbol{\Omega}_D\mathbf{H}_{D,k}^{\dagger}+\sum_{l\in\mathcal{K}_U}\mathbf{G}_{\text{UE},k,l}\mathbf{W}_{U,l}\mathbf{G}_{\text{UE},k,l}^{\dagger}$ with $\boldsymbol{\Omega}_D=\text{diag}\{\boldsymbol{\Omega}_{D,1},\ldots,\boldsymbol{\Omega}_{D,K_R}\}$. Based on the uplink signal vector $\bar{\mathbf{y}}_U$ in (7), the CU performs the MMSE-SIC decoding of the uplink messages $\{M_{U,k}\}_{k\in\mathcal{K}_U}$ by treating the D2U interference as the background noise.

Thus, the achievable uplink sum rate R_U is given by

$$R_{\Sigma}^{U}=\log\Big|\sum_{l\in\mathcal{K}_U}\boldsymbol{\Psi}_{l}^{U}+\tilde{\boldsymbol{\Phi}}^{U}\Big|-\log\Big|\tilde{\boldsymbol{\Phi}}^{U}\Big|, \quad (11)$$

where $\boldsymbol{\Psi}_{l}^{U}=\mathbf{H}_{U,l}\mathbf{W}_{U,l}\mathbf{H}_{U,l}^{\dagger}$ and $\tilde{\boldsymbol{\Phi}}^{U}=\sum_{j\in\mathcal{K}_R}\tilde{\mathbf{G}}_{R,j}\boldsymbol{\Omega}_{D,j}\tilde{\mathbf{G}}_{R,j}+\sum_{k\in\mathcal{K}_D}(\sum_{j\in\mathcal{K}_R}\tilde{\mathbf{G}}_{R,j}\mathbf{E}_j^{\dagger})\mathbf{W}_{D,k}(\sum_{j\in\mathcal{K}_R}\mathbf{E}_j\tilde{\mathbf{G}}_{R,j}^{\dagger})+\boldsymbol{\Omega}_U+\sigma_U^2\mathbf{I}$ with $\boldsymbol{\Omega}_U=\text{diag}\{\boldsymbol{\Omega}_{U,1},\ldots,\boldsymbol{\Omega}_{U,K_R}\}$. Note that when the digital SIC is not provided at all, the term $\tilde{\boldsymbol{\Phi}}^{U}$ in (11) is replaced with $\boldsymbol{\Phi}^{U}=\sum_{k\in\mathcal{K}_D}(\sum_{j\in\mathcal{K}_R}\mathbf{G}_{R,j}\mathbf{E}_j^{\dagger})\mathbf{W}_{D,k}(\sum_{j\in\mathcal{K}_R}\mathbf{E}_j\mathbf{G}_{R,j}^{\dagger})+\sum_{j\in\mathcal{K}_R}\mathbf{G}_{R,j}\boldsymbol{\Omega}_{D,j}\mathbf{G}_{R,j}+\boldsymbol{\Omega}_U+\sigma_U^2\mathbf{I}$, where $\mathbf{G}_{R,j}=[\mathbf{G}_{R,1,j}^{T},\ldots,\mathbf{G}_{R,K_R,j}^{T}]^{T}$. Also, when the SIC is performed at the CU, the term $\tilde{\boldsymbol{\Phi}}^{U}$ in (11) can be substituted by $\bar{\boldsymbol{\Phi}}^{U}=\sum_{j\in\mathcal{K}_R}\mathbf{G}_{R,j}\boldsymbol{\Omega}_{D,j}\mathbf{G}_{R,j}+\boldsymbol{\Omega}_U+\sigma_U^2\mathbf{I}+\sum_{k\in\mathcal{K}_D}(\sum_{j\in\mathcal{K}_R}\tilde{\mathbf{G}}_{R,j}\mathbf{E}_j^{\dagger})\mathbf{W}_{D,k}(\sum_{j\in\mathcal{K}_R}\mathbf{E}_j\tilde{\mathbf{G}}_{R,j}^{\dagger})$.

III. Problem Definition and Optimization

In this letter, we aim to jointly optimize the precoding covariance matrices $\mathbf{W}_D\triangleq\{\mathbf{W}_{D,k}\}_{k\in\mathcal{K}_D}$ and $\mathbf{W}_U\triangleq\{\mathbf{W}_{U,k}\}_{k\in\mathcal{K}_U}$, and the quantization noise covariance matrices $\{\boldsymbol{\Omega}_{U,i}\}_{i\in\mathcal{K}_R}$ and $\{\boldsymbol{\Omega}_{D,i}\}_{i\in\mathcal{K}_R}$ to maximize the sum-rate $R_\Sigma=R_\Sigma^D+R_\Sigma^U$ of the downlink and uplink UEs. Then, by considering the power constraints in (3) and (5) along with the fronthaul capacity limits given in (2) and (8), the problem can be stated as

$$\begin{aligned}\max_{\mathbf{W}_D,\mathbf{W}_U,\boldsymbol{\Omega}_D,\boldsymbol{\Omega}_U}\quad & R_\Sigma^D+R_\Sigma^U\\ \text{s.t.}\quad & (2),\ (3),\ (5),\ (8),\\ & \boldsymbol{\Omega}_{D,i}\succeq\mathbf{0},\ \ \boldsymbol{\Omega}_{U,i}\succeq\mathbf{0},\forall i\in\mathcal{K}_R\\ & \mathbf{W}_{D,k}\succeq\mathbf{0},\forall k\in\mathcal{K}_D,\mathbf{W}_{U,l}\succeq\mathbf{0},\forall l\in\mathcal{K}_U.\end{aligned} \quad (12)$$

Since there exist the combination of D2U and U2D interference, the problem is non-convex with respect to $\mathbf{W}_D,\mathbf{W}_U,\boldsymbol{\Omega}_D,$ and $\boldsymbol{\Omega}_U$ in general. However, we observe that problem (12) has a difference-of-convex (DC) form in the objective function and the constraints. Hence, we now propose a MM based algorithm, which solves a sequence of convex problems by linearizing the original non-convex functions in (12) at each iteration [9].

Algorithm 1 MM Algorithm for Problem (12)

1: Initialize $\mathbf{W}_D^{(1)}$, $\mathbf{W}_U^{(1)}$, $\boldsymbol{\Omega}_D^{(1)}$ and $\boldsymbol{\Omega}_U^{(1)}$ and set $t=1$.
2: **repeat**
3: Update $\mathbf{W}_D^{(t+1)}$, $\mathbf{W}_U^{(t+1)}$, $\boldsymbol{\Omega}_D^{(t+1)}$ and $\boldsymbol{\Omega}_U^{(t+1)}$ as a solution of the convex problem (13).
4: Set $t\leftarrow t+1$
5: **until** a convergence criterion of sum-rate is satisfied.
6: Apply Cholesky decomposition $\mathbf{W}_{D,k}=\mathbf{V}_{D,k}\mathbf{V}_{D,k}^{\dagger}$ and $\mathbf{W}_{U,l}=\mathbf{V}_{U,l}\mathbf{V}_{U,l}^{\dagger}$, and calculate the precoding matrices $\mathbf{V}_{D,k}=\mathbf{A}_{D,k}\mathbf{D}_{D,k}^{1/2}$ and $\mathbf{V}_{U,l}=\mathbf{A}_{U,l}\mathbf{D}_{U,l}^{1/2}$ for $k\in\mathcal{K}_D$ and $l\in\mathcal{K}_U$, where $\mathbf{D}_{D,k}$ and $\mathbf{D}_{U,k}$ are diagonal matrices whose diagonal elements are the nonzero eigenvalues of $\mathbf{W}_{D,k}^{(t+1)}$ and $\mathbf{W}_{U,k}^{(t+1)}$ and the columns of $\mathbf{A}_{D,k}$ and $\mathbf{A}_{U,k}$ are the corresponding eigenvectors.

To this end, we first note that $\log|\mathbf{X}^{(t+1)}|$ can be linearized by utilizing the first-order Taylor series approximation as $\varphi(\mathbf{X}^{(t+1)},\mathbf{X}^{(t)})\triangleq\log|\mathbf{X}^{(t)}|+\frac{1}{\ln 2}\text{tr}((\mathbf{X}^{(t)})^{-1}(\mathbf{X}^{(t+1)}-\mathbf{X}^{(t)}))$ where $\mathbf{X}^{(t+1)}$ is the current optimizing variable at iteration $t+1$ based on the previously updated $\mathbf{X}^{(t)}$. Then, by defining $\boldsymbol{\Gamma}^{(t)}=\{\{\mathbf{W}_{D,k}^{(t)}\}_{k\in\mathcal{K}_D},\ \{\mathbf{W}_{U,k}^{(t)}\}_{k\in\mathcal{K}_U},\ \{\boldsymbol{\Omega}_{U,i}^{(t)}\}_{i\in\mathcal{K}_R},\ \{\boldsymbol{\Omega}_{D,i}^{(t)}\}_{i\in\mathcal{K}_R}\}$ as a set of all input variables that are updated at iteration t, we can obtain a new $\boldsymbol{\Gamma}^{(t+1)}$ through solving the following convexified problem at iteration $t+1$ as

$$\begin{aligned}\max_{\boldsymbol{\Gamma}^{(t+1)}}\quad & \hat{R}_\Sigma^D(\boldsymbol{\Gamma}^{(t+1)},\boldsymbol{\Gamma}^{(t)})+\hat{R}_\Sigma^U(\boldsymbol{\Gamma}^{(t+1)},\boldsymbol{\Gamma}^{(t)})\\ \text{s.t.}\quad & \hat{g}_{D,i}(\boldsymbol{\Gamma}^{(t+1)},\boldsymbol{\Gamma}^{(t)})\le C_{D,i},\forall i\in\mathcal{K}_R,\\ & \hat{g}_{U,i}(\boldsymbol{\Gamma}^{(t+1)},\boldsymbol{\Gamma}^{(t)})\le C_{U,i},\forall i\in\mathcal{K}_R,\\ & \text{tr}\Big(\sum_{k\in\mathcal{K}_D}\mathbf{E}_i^{\dagger}\mathbf{W}_{D,k}^{(t+1)}\mathbf{E}_i+\boldsymbol{\Omega}_{D,i}\Big)\le P_{R,i},\forall i\in\mathcal{K}_R,\\ & \boldsymbol{\Omega}_{D,i}\succeq\mathbf{0},\ \ \boldsymbol{\Omega}_{U,i}\succeq\mathbf{0},\forall i\in\mathcal{K}_R,\mathbf{W}_{D,k}\succeq\mathbf{0},\forall k\in\mathcal{K}_D,\\ & \text{tr}\Big(\mathbf{W}_{U,l}^{(t+1)}\Big)\le P_{U,l},\mathbf{W}_{U,l}\succeq\mathbf{0},\forall l\in\mathcal{K}_U,\end{aligned} \quad (13)$$

where $\hat{R}_\Sigma^D(\cdot)$, $\hat{R}_\Sigma^U(\cdot)$, $\hat{g}_{D,i}(\cdot)$, and $\hat{g}_{U,i}(\cdot)$ are the linearized functions of (10), (11), (2), and (8), respectively, using the first-order Taylor series approximation.

Specifically, at the bottom of this page, we define $\hat{R}_\Sigma^D(\cdot)$ as in (14), where $\boldsymbol{\Psi}_{k,l}^{D,(t)}$ and $\boldsymbol{\Phi}_{k}^{D,(t)}$ are denoted as $\boldsymbol{\Psi}_{k,l}^{D,(t)}=\mathbf{H}_{D,k}\mathbf{W}_{D,l}^{(t)}\mathbf{H}_{D,k}^{\dagger}$, $\boldsymbol{\Phi}_{k}^{D,(t)}=\sum_{l\in\mathcal{K}_U}\mathbf{G}_{\text{UE},k,l}\mathbf{W}_{U,l}^{(t)}\mathbf{G}_{\text{UE},k,l}^{\dagger}+\mathbf{H}_{D,k}\boldsymbol{\Omega}_D^{(t)}\mathbf{H}_{D,k}^{\dagger}+\sigma_D^2\mathbf{I}$, respectively. Similarly, $\hat{R}_\Sigma^U(\cdot)$ is expressed in (15) with the updated covariance matrices $\boldsymbol{\Psi}_{l}^{U,(t)}=\mathbf{H}_{U,l}\mathbf{W}_{U,l}^{(t)}\mathbf{H}_{U,l}^{\dagger}$ and $\tilde{\boldsymbol{\Phi}}^{U,(t)}=\boldsymbol{\Omega}_U^{(t)}+\sigma_U^2\mathbf{I}+\sum_{k\in\mathcal{K}_D}(\sum_{j\in\mathcal{K}_R}\tilde{\mathbf{G}}_{\text{RU},j}\mathbf{E}_j^{\dagger})\mathbf{W}_{D,k}^{(t)}(\mathbf{E}_j\sum_{j\in\mathcal{K}_R}\tilde{\mathbf{G}}_{\text{RU},j}^{\dagger})+\sum_{j\in\mathcal{K}_R}\tilde{\mathbf{G}}_{\text{RU},j}\boldsymbol{\Omega}_{D,j}^{(t)}\tilde{\mathbf{G}}_{\text{RU},j}$. Also, the convexified front-haul capacity functions $\hat{g}_{D,i}(\cdot)$ and $\hat{g}_{D,i}(\cdot)$ are shown in (16)

$$\hat{R}_\Sigma^D(\boldsymbol{\Gamma}^{(t)},\boldsymbol{\Gamma}^{(t+1)})\triangleq\sum_{k\in\mathcal{K}_D}\log\Big|\sum_{l\in\mathcal{K}_D}\boldsymbol{\Psi}_{k,l}^{D,(t+1)}+\boldsymbol{\Phi}_{k}^{D,(t+1)}\Big|-\sum_{k\in\mathcal{K}_D}\varphi\Big(\sum_{l\in\mathcal{K}_D\backslash\{k\}}\boldsymbol{\Psi}_{k,l}^{D,(t+1)}+\boldsymbol{\Phi}_{k}^{D,(t+1)},\sum_{l\in\mathcal{K}_D\backslash\{k\}}\boldsymbol{\Psi}_{k,l}^{D,(t)}+\boldsymbol{\Phi}_{k}^{D,(t)}\Big), \quad (14)$$

$$\hat{R}_\Sigma^U(\boldsymbol{\Gamma}^{(t)},\boldsymbol{\Gamma}^{(t+1)})\triangleq\log\Big|\sum_{l\in\mathcal{K}_U}\boldsymbol{\Psi}_{l}^{U,(t+1)}+\tilde{\boldsymbol{\Phi}}^{U,(t+1)}\Big|-\varphi\Big(\tilde{\boldsymbol{\Phi}}^{U,(t+1)},\tilde{\boldsymbol{\Phi}}^{U,(t)}\Big), \quad (15)$$

$$\hat{g}_{D,i}(\boldsymbol{\Gamma}^{(t)},\boldsymbol{\Gamma}^{(t+1)})\triangleq\varphi\Big(\sum_{k\in\mathcal{K}_D}\mathbf{E}_i^{\dagger}\mathbf{W}_{D,k}^{(t+1)}\mathbf{E}_i+\boldsymbol{\Omega}_{D,i}^{(t+1)},\sum_{k\in\mathcal{K}_D}\mathbf{E}_i^{\dagger}\mathbf{W}_{D,k}^{(t)}\mathbf{E}_i+\boldsymbol{\Omega}_{D,i}^{(t)}\Big)-\log\Big|\boldsymbol{\Omega}_{D,i}^{(t+1)}\Big|, \quad (16)$$

$$\hat{g}_{U,i}(\boldsymbol{\Gamma}^{(t)},\boldsymbol{\Gamma}^{(t+1)})\triangleq\varphi\Big(\sum_{k\in\mathcal{K}_U}\boldsymbol{\Psi}_{U,i,k}^{(t+1)}+\tilde{\boldsymbol{\Theta}}_i^{(t+1)}+\boldsymbol{\Omega}_{U,i}^{(t+1)}+\sigma_U^2\mathbf{I},\sum_{k\in\mathcal{K}_U}\boldsymbol{\Psi}_{U,i,k}^{(t)}+\tilde{\boldsymbol{\Theta}}_i^{(t)}+\boldsymbol{\Omega}_{U,i}^{(t)}+\sigma_U^2\mathbf{I}\Big)-\log\Big|\boldsymbol{\Omega}_{U,i}^{(t+1)}\Big|. \quad (17)$$

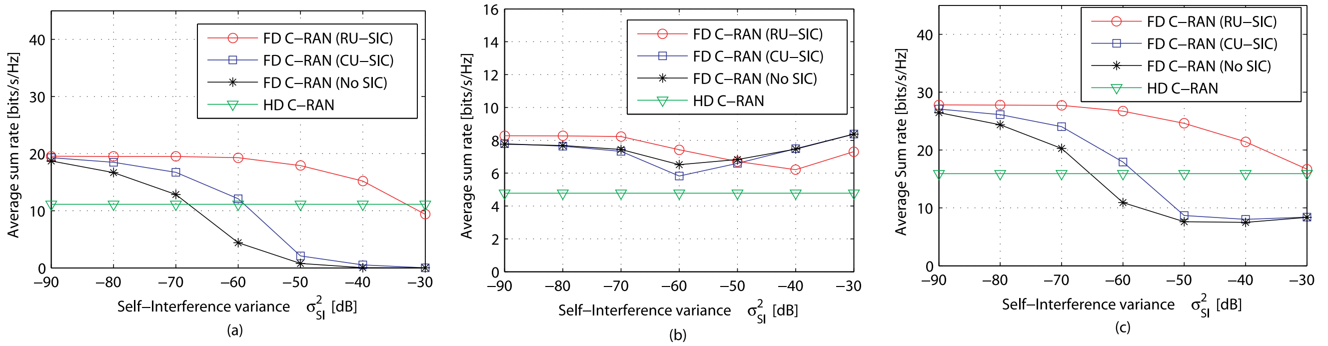

Fig. 1. Average sum rate versus $\sigma_{\rm SI}^2$ for the FD systems. (a) Average sum rate of the uplink UEs, (b) Average sum rate of the downlink UEs, (c) Average sum rate of the entire UEs.

and (17), as shown at the bottom of the previous page, respectively, with the updated covariance matrices $\mathbf{\Psi}_{{\rm UL},i,k}^{(t)} = \mathbf{H}_{U,i,k}\mathbf{W}_{U,k}^{(t)}\mathbf{H}_{U,i,k}^{\dagger}$, $\tilde{\mathbf{\Theta}}_i^{(t)} = \sum_{j\in\mathcal{K}_R\setminus\{i\}}\mathbf{G}_{{\rm RU},i,j}\mathbf{\Omega}_{D,j}^{(t)}\mathbf{G}_{{\rm RU},i,j}^{\dagger} + \tilde{\mathbf{G}}_{{\rm RU},i,i}\mathbf{\Omega}_{D,i}^{(t)}\tilde{\mathbf{G}}_{{\rm RU},i,i}^{\dagger} + \sum_{k\in\mathcal{K}_D}\bar{\mathbf{G}}_i\mathbf{W}_{D,k}^{(t)}\bar{\mathbf{G}}_i^{\dagger}$. The detailed algorithm is summarized in Algorithm 1.

IV. Numerical Results

In this section, we provide some numerical results to evaluate the performance of the proposed FD C-RAN scheme and compare with that of other conventional systems. Throughout the simulation, we assume $K_R = 4$, $N_{R,D} = N_{R,U} = 2$, $K_D = K_U = 4$, and $N_D = N_U = 2$. Downlink UEs and uplink UEs are uniformly distributed within a squared area of side length 100 m, while each of 4 RUs is located at the center of 4 equally divided squared small-cells and thus the distance among 4 RUs equals 50 m. Also, while noise power is -107 dBm, the maximum transmit power at each RU and uplink UE are 26 dBm and 23 dBm, respectively. Since the receive antennas of each RU are closely placed next to its transmit antennas, the elements of the SI channel matrices $\mathbf{G}_{{\rm RU},i,i}$ are characterized by a Rician distribution with mean $\sqrt{\sigma_{\rm SI}^2\kappa/(1+\kappa)}$ and variance $\sigma_{\rm SI}^2/(1+\kappa)$ [4], where κ and $\sigma_{\rm SI}^2$ equal the Rician factor and the amount of residual SI power in digital domain, respectively. Similarly, the entries of the effective SI channel matrices $\tilde{\mathbf{G}}_{{\rm RU},i,i}$, which are mitigated by the additional digital SIC, are modeled by a Rician distribution with much reduced SI power $\tilde{\sigma}_{\rm SI}^2 \ll \sigma_{\rm SI}^2$. In this simulation, we set a gain of the digital SIC as $10\log_{10}(\frac{\sigma_{\rm SI}^2}{\tilde{\sigma}_{\rm SI}^2}) = 35$ dB. The rest of channel matrices follows a complex Gaussian distribution with path-loss defined as ${\rm PL} = 22.9 + 37.5\log_{10} d$ in dB where d is the distance in meters between relevant entities.

Based on the proposed algorithm, we compare three different strategies and the HD scheme: i) "RU-SIC": the digital SIC is performed with 35 dB gain at RU, ii) "CU-SIC": the digital SIC is applied with a 35 dB gain at CU, iii) "No SIC": the digital SIC is not employed at any entities, and iv) HD C-RAN with point-to-point compression [10].

For insightful comparison between the FD and HD C-RAN systems, Fig. 1 depicts the sum-rate performance of the downlink, uplink, and entire transmissions in Fig. 1 (a), (b), and (c), respectively, as a function of $\sigma_{\rm SI}^2$ under the front-haul capacity constraints of $C_{D,i} = C_{U,i} = 5$ bits/s/Hz. In Fig. 1 (a), we can see that the sum-rate of the uplink transmissions obviously decreases as SI power $\sigma_{\rm SI}^2$ increases. Specifically, "RU-SIC" significantly improves the uplink spectral efficiency over other conventional FD schemes "CU-SIC" and "No SIC" in all ranges of σ_{SI}^2. On the other hand, in Fig. 1 (b), the sum rates of downlink transmission for "No SIC", "CU-SIC", and "RU-SIC" decrease up to different certain values of σ_{SI}^2 and then increases again. The reason is that if the SI is sufficiently mitigated so that $\sigma_{\rm SI}^2$ is small, the joint optimization schemes for FD systems can reduce the transmit power of the downlink transmission to maintain the sum-rate of the uplink transmission. In contrast, when the SI power gets non-negligibly higher, it becomes difficult to increase the uplink sum-rate. Thus, in this case, the joint optimization schemes reduce the power of uplink UEs, i.e., the power of U2D interference, in order to focus on maximizing downlink sum rate. In Fig. 1 (c), we observe that at $\sigma_{SI}^2 = -50$ dB, the proposed "RU-SIC" outperforms "CU-SIC" and "No SIC" by 215% and 176%, respectively. In fact, in this case, the sum rate performance of the conventional FD schemes is even worse than that of the HD C-RAN, while the proposed "RU-SIC" is still superior to the HD system. Hence, we can conclude that the proposed FD C-RAN system with SIC implemented at RUs brings significant sum-rate gains over the conventional schemes.

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