Fronthaul Compression and Precoding Design for MIMO Full-duplex Cognitive Radio Networks

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***Abstract*—In this work, joint design of fronthaul compression and precoding in cloud radio access networks (C-RANs) is studied for full-duplex (FD) multiple-input multiple-output (MIMO) underlay cognitive radio networks. In this system, multiple secondary uplink (UL) and downlink (DL) users equipped with multiple antennas communicate with a control unit (CU) in the "cloud" through a set of multi-antenna secondary FD radio units (RU) which are connected to the CU through limited capacity links. We address the sum-rate maximization problem subject to UL and DL fronthaul rate constraints at each RU, power constraints at each RU and UL users, and maximum allowed interference at the primary users. Casting this non-convex problem as a difference of convex (DC) problem, an iterative algorithm based on the Majorization Minimization (MM) approach that guarantees convergence to a stationary point is proposed. Numerical results demonstrate the advantage of the proposed algorithm.**

***Keywords*—Cognitive radio, full-duplex, MIMO, multi-user, self-interference.**

I. Introduction

In current wireless communication systems, downlink (DL) and uplink (UL) channels are designed to operate in half-duplex (HD) mode, i.e., orthogonal channels. Full-duplex (FD) communication, which enables UL and DL communication at the same time slot on the same frequency, is a promising technique to double the spectral efficiency [1]. Although there are several designs to deal with the self-interference inherent in FD radios, due to the imperfections of radio devices, the self-interference cannot be canceled completely in reality [2].

On a parallel avenue, cloud radio access networks (C-RANs) have emerged as a novel mobile network architecture for next-generation wireless cellular systems that migrate the baseband operations of a cluster of radio units (RUs) to a centralized control unit (CU) via finite-capacity fronthaul links [3]. Since the fronthaul links typically have limited capacity and are known to impose a formidable bottleneck to the system performance, it is important to carefully design precoding and fronthaul compression strategies to achieve a high spectral efficiency [3].

Furthermore, cognitive radio system is another promising technology that can enhance spectrum efficiency [4]. In an underlay cognitive radio system, unlicensed secondary users can access the spectrum owned by the licensed primary users as long as the interference level from secondary to primary users is under a predetermined level.

In this work, we combine these three promising technologies, and consider an C-RAN system where underlay secondary RUs operating in FD mode serve multiple secondary UL and DL users simultaneously within the service range of multiple primary users, and connect to a CU via finite-capacity fronthaul links to transfer the interference management task to be done by the centralized baseband processing effectively. The significant potential advantages of FD in the C-RAN architecture with sufficient fronthaul capacity and appropriate scheduling was analyzed in [5]. Combining the benefits of FD transmission at RUs with the FD fronthaul leads to efficient reuse of RAN spectrum, alleviates the need to obtain dedicated spectrum for fronthaul, and facilitates hardware implementation by enabling the use of same hardware for access links and fronthaul links. While the FD operation can ideally double the spectral efficiency in a link, the network-level gain of exploiting FD transmission in the fronthaul remains unclear due to the complicated interference environments, e.g., self-interference, co-channel interferences (CCI) at the fronthaul and access links. Therefore, the use of FD fronthaul is not immediately evident over the popular HD fronthaul [6].

This paper studies the sum-rate maximization on the UL and DL channels subject to finite fronthaul rate constraints at each RU, power constraints at the RUs and ULs, and the interference power constraint from the secondary to the primary users, to find the optimal transmit beamformers and quantization noise covariance matrices. With the observation that this non-convex problem can be cast as a difference-of-convex (DC) problem [7], we employ an iterative algorithm converging to a stationary point based on the majorization minimization (MM) approach, which solves a sequence of convex problems obtained by linearizing the non-convex parts in the original problem [7], [8]. The simulation results show the enhancement of the spectral efficiency, thanks to the FD operation of radio units, compared to a HD C-RAN system. Moreover, the coordination of RUs result in a better coexistence with a primary network in the downlink, and enhances the performance of the cognitive radio system.

Notation: Matrices and vectors are denoted as bold capital and lowercase letters, respectively. $(\cdot)^T$ is the transpose, and $(\cdot)^H$ is the conjugate transpose. $\mathbf{I}_N$ is the N by N identity matrix, and $\mathbf{0}_{N\times M}$ is the N by M zero matrix. tr$\{\cdot\}$ is the trace, $|\cdot|$ is the determinant. $\mathbb{C}^{M\times N}$ denotes the set of complex matrices with a dimension of $M\times N$, $\mathcal{CN}\left(\mu,\sigma^2\right)$ denotes complex Gaussian distribution with mean μ and variance σ^2,

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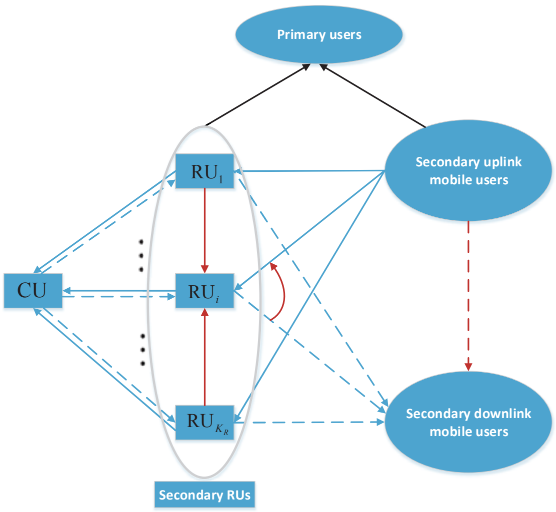

Fig. 1. Full-duplex cognitive cloud radio access network. The solid and dashed lines refer to uplink and downlink transmission, respectively.

and $\text{diag}\{a_1, \cdots, a_n\}$ denotes a diagonal matrix with the diagonal elements given by $a_1, \cdots, a_n$.

II. System Model

We consider an C-RAN system, similar to the model in [8], where a CU is connected to K_{RU} secondary FD RUs through wired finite-capacity fronthaul links as shown in Fig. 1. The RUs serve K_{UL} UL and K_{DL} DL secondary users simultaneously within the range of K_{PU} primary users. The kth FD RU is equipped with M_k transmit and N_k receive antennas with a total of $M^{DL} = \sum_{k=1}^{K_{RU}} M_k$ transmit and $N^{UL} = \sum_{k=1}^{K_{RU}} N_k$ receive antennas at the RUs. The number of antennas at the kth UL and DL users are T_k and R_k, respectively, and the kth primary user has P_k receive antennas. Let us denote $\mathcal{S}^{UL}$, $\mathcal{S}^{DL}$, $\mathcal{S}^{RU}$, and $\mathcal{S}^{PU}$ as the set of all UL, DL users, RUs, and primary users, respectively.

A. Downlink System

In the DL system, the transmit signal vector at the CU $\tilde{\mathbf{x}}^{DL} = \left[\left(\tilde{\mathbf{x}}_1^{DL}\right)^T, \ldots, \left(\tilde{\mathbf{x}}_{K_{RU}}^{DL}\right)^T \right]^T \in \mathbb{C}^{M^{DL} \times 1}$ is expressed as

$$\tilde{\mathbf{x}}^{DL} = \sum_{k=1}^{K_{DL}} \mathbf{V}_k^{DL} \mathbf{s}_k^{DL}. \tag{1}$$

Here $\mathbf{V}_k^{DL} \in \mathbb{C}^{M^{DL} \times d_k^{DL}}$ denotes the precoding matrix for the data symbol of the kth DL user represented as $\mathbf{s}_k^{DL} \in \mathbb{C}^{d_k^{DL} \times 1} \sim \mathcal{CN}\left(\mathbf{0}, \mathbf{I}_{d_k^{DL}}\right)$, where d_k^{DL} is the number of data streams destined to the kth DL user, $k \in \mathcal{S}^{DL}$. The vector transfered from the CU to the ith RU is the ith subvector of $\tilde{\mathbf{x}}^{DL}$ denoted as $\tilde{\mathbf{x}}_i^{DL} = \mathbf{E}_i^H \tilde{\mathbf{x}}^{DL}$, where $\mathbf{E}_i$ is defined as

$$\mathbf{E}_i = \left[\mathbf{0}^T_{\sum_{k=1}^{i-1} M_k \times M_i}, \ \mathbf{I}^T_{M_i \times M_i}, \ \mathbf{0}^T_{\sum_{k=i+1}^{K_{RU}} M_k \times M_i} \right]^T.$$

The CU compresses the baseband signal $\tilde{\mathbf{x}}_i^{DL}$ by quantizing and forwards on the fronthaul links to the corresponding RUs. The received signal at the ith RU is given as

$$\mathbf{x}_i^{DL} = \tilde{\mathbf{x}}_i^{DL} + \mathbf{q}_i^{DL}, \ i \in \mathcal{S}^{RU}, \tag{2}$$

where $\mathbf{q}_i^{DL} \sim \mathcal{CN}\left(\mathbf{0}, \ \boldsymbol{\Upsilon}_i^{DL}\right)$ is the quantization noise at the ith RU in the DL channel. Given (2), the DL fronthaul rate and power constraints at the ith RU are given, respectively, as

$$\log \left| \mathbf{E}_i^H \sum_{k=1}^{K_{DL}} \mathbf{Q}_k^{DL} \mathbf{E}_i + \boldsymbol{\Upsilon}_i^{DL} \right| - \log \left| \boldsymbol{\Upsilon}_i^{DL} \right| \leq C_i^{DL}, \ i \in \mathcal{S}^{RU} \tag{3}$$

$$\text{tr} \left\{ \mathbf{E}_i^H \sum_{k=1}^{K_{DL}} \mathbf{Q}_k^{DL} \mathbf{E}_i + \boldsymbol{\Upsilon}_i^{DL} \right\} \leq P_i^{DL}, \ i \in \mathcal{S}^{RU}, \tag{4}$$

where $\mathbf{Q}_k^{DL} = \mathbf{V}_k^{DL} \left(\mathbf{V}_k^{DL}\right)^H$ is the source covariance matrix of the kth DL user, and C_i^{DL} and P_i^{DL} are the DL fronthaul rate and power constraints at the ith RU, respectively.

The received signal at the kth DL user is expressed as

$$\mathbf{y}_k^{DL} = \mathbf{H}_k^{DL} \mathbf{x}^{DL} + \sum_{l=1}^{K_{UL}} \mathbf{H}_{kl}^{DU} \mathbf{x}_l^{UL} + \mathbf{n}_k^{DL}, \ k \in \mathcal{S}^{DL}, \tag{5}$$

where $\mathbf{H}_{ki}^{DL} \in \mathbb{C}^{R_k \times M_i}$ represents the channel matrix from the ith RU to the kth DL user, and the stacked matrix $\mathbf{H}_k^{DL} \in \mathbb{C}^{R_k \times M^{DL}}$ is denoted as $\mathbf{H}_k^{DL} = \left[\mathbf{H}_{k1}^{DL}, \ldots, \mathbf{H}_{kK_{RU}}^{DL}\right]$. Moreover, $\mathbf{H}_{kl}^{DU} \in \mathbb{C}^{R_k \times T_l}$ denotes the co-channel interference (CCI) channel from the lth UL user to the kth DL user. The stacked transmit vector is denoted as $\mathbf{x}^{DL} = \left[\left(\mathbf{x}_1^{DL}\right)^T, \ldots, \left(\mathbf{x}_{K_{RU}}^{DL}\right)^T \right]^T \in \mathbb{C}^{M^{DL} \times 1}$, and $\mathbf{x}_l^{UL} \in \mathbb{C}^{T_l \times 1}$ is the transmit signal vector of the lth UL user. Finally, $\mathbf{n}_k^{DL} \sim \mathcal{CN}\left(\mathbf{0}, \ \sigma_{DL}^2 \mathbf{I}_{R_k}\right)$ denotes the additive white Gaussian noise (AWGN) at the kth DL user.

Given (5), the achievable rate at the kth DL user, $k \in \mathcal{S}^{DL}$ is given as

$$R_k^{DL} = \log \left| \mathbf{H}_k^{DL} \mathbf{Q}_k^{DL} \left(\mathbf{H}_k^{DL}\right)^H + \boldsymbol{\Sigma}_k^{DL} \right| - \log \left| \boldsymbol{\Sigma}_k^{DL} \right|, \tag{6}$$

where $\boldsymbol{\Sigma}_k^{DL}$ is the interference-plus-noise covariance matrix at the kth DL user, $k \in \mathcal{S}^{DL}$, and is expressed as

$$\boldsymbol{\Sigma}_k^{DL} = \mathbf{H}_k^{DL} \sum_{l=1, l \neq k}^{K_{DL}} \mathbf{Q}_l^{DL} \left(\mathbf{H}_k^{DL}\right)^H + \sum_{l=1}^{K_{UL}} \mathbf{H}_{kl}^{DU} \mathbf{Q}_l^{UL} \left(\mathbf{H}_{kl}^{DU}\right)^H + \mathbf{H}_k^{DL} \text{diag}\left\{\boldsymbol{\Upsilon}_1^{DL}, \ldots, \boldsymbol{\Upsilon}_{K_{RU}}^{DL}\right\} \left(\mathbf{H}_k^{DL}\right)^H + \sigma_{DL}^2 \mathbf{I}_{R_k}.$$

B. Uplink System

In the UL channel, the received signal at the ith RU is given as

$$\mathbf{y}_i^{UL} = \sum_{k=1}^{K_{UL}} \mathbf{H}_{ik}^{UL} \mathbf{V}_k^{UL} \mathbf{s}_k^{UL} + \sum_{j=1}^{K_{RU}} \mathbf{H}_{ij}^{UD} \mathbf{x}_j^{DL} + \mathbf{n}_i^{UL}, \ i \in \mathcal{S}^{RU} \tag{7}$$

where $\mathbf{V}_k^{UL} \in \mathbb{C}^{T_k \times d_k^{UL}}$ denotes the precoding matrix for the data symbol of the kth UL user represented as $\mathbf{s}_k^{UL} \in \mathbb{C}^{d_k^{UL} \times 1} \sim \mathcal{CN}\left(\mathbf{0}, \mathbf{I}_{d_k^{UL}}\right)$, where d_k^{UL} is the number of data streams of the kth UL user. Here, $\mathbf{H}_{ik}^{UL} \in \mathbb{C}^{N_i \times T_k}$ represents the channel matrix from kth UL user to the ith RU, and $\mathbf{H}_{ij}^{UD} \in \mathbb{C}^{N_i \times M_j}$ represents the channel matrix from the jth RU to the ith RU. Note that when $i = j$, $\mathbf{H}_{ii}^{UD}$ is the residual self-interference channel at the ith RU obtained after canceling the downlink signal at the uplink channel. Finally, the vector $\mathbf{n}_i^{UL} \sim \mathcal{CN}\left(\mathbf{0},\ \sigma_{UL}^2 \mathbf{I}_{N_i}\right)$ denotes the AWGN at the ith RU. The power constraint at the kth UL user is given as

$$\mathrm{tr}\left\{\mathbf{Q}_k^{UL}\right\} \leq P_k^{UL},\ k \in \mathcal{S}^{UL}, \tag{8}$$

where $\mathbf{Q}_k^{UL} = \mathbf{V}_k^{UL}\left(\mathbf{V}_k^{UL}\right)^H$ and P_k^{UL} are the source covariance matrix and the maximum allowed transmit power at the kth UL user, respectively.

Upon receiving the signal (7), the ith RU forwards the compressed version of the signal (7) to the CU, given as

$$\tilde{\mathbf{y}}_i^{UL} = \mathbf{y}_i^{UL} + \mathbf{q}_i^{UL},\ i \in \mathcal{S}^{RU}, \tag{9}$$

where $\mathbf{q}_i^{UL} \sim \mathcal{CN}\left(\mathbf{0},\ \mathbf{\Upsilon}_i^{UL}\right)$ is the quantization noise at the ith RU in the UL channel. Given (9), the CU can recover the signal of the ith RU only when the following UL fronthaul rate condition is satisfied:

$$\log\left|\mathbf{\Phi}_i^{UL} + \mathbf{\Upsilon}_i^{UL}\right| - \log\left|\mathbf{\Upsilon}_i^{UL}\right| \leq C_i^{UL},\ i \in \mathcal{S}^{RU}, \tag{10}$$

where C_i^{UL} is the UL fronthaul rate constraint at the ith RU, and $\mathbf{\Phi}_i^{UL}$ is the covariance matrix of the received signal $\mathbf{y}_i^{UL}$ in (7) given as

$$\begin{aligned}\mathbf{\Phi}_i^{UL} = &\sum_{k=1}^{K_{UL}} \mathbf{H}_{ik}^{UL}\mathbf{Q}_k^{UL}\left(\mathbf{H}_{ik}^{UL}\right)^H + \sigma_{UL}^2\mathbf{I}_{N_i}\\ &+ \sum_{k=1}^{K_{DL}}\left(\sum_{j=1}^{K_{RU}}\mathbf{H}_{ij}^{UD}\mathbf{E}_j^H\right)\mathbf{Q}_k^{DL}\left(\sum_{m=1}^{K_{RU}}\mathbf{E}_m\left(\mathbf{H}_{im}^{UD}\right)^H\right)\\ &+ \sum_{j=1}^{K_{RU}}\mathbf{H}_{ij}^{UD}\mathbf{\Upsilon}_j^{DL}\left(\mathbf{H}_{ij}^{UD}\right)^H.\end{aligned} \tag{11}$$

Stacking the received signal vectors at the CU as $\tilde{\mathbf{y}}^{UL} = \left[\left(\tilde{\mathbf{y}}_1^{UL}\right)^T, \ldots, \left(\tilde{\mathbf{y}}_{K_{RU}}^{UL}\right)^T\right]^T$, and applying the minimum mean squared error decoding with successive interference cancellation (MMSE-SIC), the achievable UL sum-rate is given as [9]:

$$R^{UL} = \log\left|\sum_{k=1}^{K_{UL}}\mathbf{H}_k^{UL}\mathbf{Q}_k^{UL}\left(\mathbf{H}_k^{UL}\right)^H + \mathbf{\Sigma}^{UL}\right| - \log\left|\mathbf{\Sigma}^{UL}\right| \tag{12}$$

where $\mathbf{\Sigma}^{UL}$ is the interference-plus-noise covariance matrix and is expressed as

$$\begin{aligned}\mathbf{\Sigma}^{UL} = &\sum_{k=1}^{K_{DL}}\left(\sum_{j=1}^{K_{RU}}\mathbf{H}_j^{UD}\mathbf{E}_j^H\right)\mathbf{Q}_k^{DL}\left(\sum_{i=1}^{K_{RU}}\mathbf{E}_i\left(\mathbf{H}_i^{UD}\right)^H\right)\\ &+ \sum_{j=1}^{K_{RU}}\mathbf{H}_j^{UD}\mathbf{\Upsilon}_j^{DL}\left(\mathbf{H}_j^{UD}\right)^H + \sigma_{UL}^2\mathbf{I}_{N^{UL}}\\ &+ \mathrm{diag}\left\{\mathbf{\Upsilon}_1^{UL}, \ldots, \mathbf{\Upsilon}_{K_{RU}}^{UL}\right\}.\end{aligned}$$

The stacked channel matrices in (12) and (13) are denoted as $\mathbf{H}_k^{UL} = \left[\left(\mathbf{H}_{1k}^{UL}\right)^T, \ldots, \left(\mathbf{H}_{K_{RU}k}^{UL}\right)^T\right]^T$ and $\mathbf{H}_j^{UD} = \left[\left(\mathbf{H}_{1j}^{UD}\right)^T, \ldots, \left(\mathbf{H}_{K_{RU}j}^{UD}\right)^T\right]^T$, respectively.

Since the secondary and primary networks coexist under the same spectrum, secondary network infers interference on the primary network. The interference power constraint from the secondary UL users and RUs projected to the lth primary user is written as

$$\begin{aligned}\mathrm{tr}\Bigg\{&\tilde{\mathbf{H}}_l^{DL}\left(\sum_{k=1}^{K_{DL}}\mathbf{Q}_k^{DL} + \mathrm{diag}\left\{\mathbf{\Upsilon}_1^{DL}, \ldots, \mathbf{\Upsilon}_{K_{RU}}^{DL}\right\}\right)\left(\tilde{\mathbf{H}}_l^{DL}\right)^H\\ &+ \sum_{k=1}^{K_{UL}}\tilde{\mathbf{H}}_{lk}^{UL}\mathbf{Q}_k^{UL}\left(\tilde{\mathbf{H}}_{lk}^{UL}\right)^H\Bigg\} \leq \lambda_l,\ l \in \mathcal{S}^{PU},\end{aligned} \tag{13}$$

where the stacked matrix $\tilde{\mathbf{H}}_l^{DL} \in \mathbb{C}^{P_l \times M^{DL}}$ is denoted as $\tilde{\mathbf{H}}_l^{DL} = \left[\tilde{\mathbf{H}}_{l1}^{DL}, \ldots, \tilde{\mathbf{H}}_{lK_{RU}}^{DL}\right]$, and $\tilde{\mathbf{H}}_{lk}^{DL} \in \mathbb{C}^{P_l \times M_k}$ represents the channel between the lth primary user and the kth RU. Moreover, $\tilde{\mathbf{H}}_{lk}^{UL} \in \mathbb{C}^{P_l \times T_k}$ is the channel between the lth primary user and the kth UL user. Here, λ_l in (13) is the upper limit of the interference allowed to be imposed on the lth primary user.

III. Joint Design

In this section, we jointly optimize the source and quantization noise covariance matrices to maximize the sum-rate of the FD C-RAN system subject to power constraints in (4) and (8), fronthaul rate constraints in (3) and (10), and interference power constraints in (13). The problem is formulated as:

$$\begin{aligned}\max_{\mathbf{Q},\mathbf{\Upsilon}}\quad & \sum_{k=1}^{K_{DL}} R_k^{DL} + R^{UL} && \text{(14a)}\\ \text{s.t.}\quad & (3),\ (4),\ (8),\ (10),\ (13) && \text{(14b)}\\ & \mathbf{\Upsilon}_i^X \succeq \mathbf{0},\ i \in \mathcal{S}^{RU},\ X \in \{UL, DL\}, && \text{(14c)}\\ & \mathbf{Q}_k^X \succeq \mathbf{0},\ k \in \mathcal{S}^X,\ X \in \{UL, DL\}. && \text{(14d)}\end{aligned}$$

Here, the variables $\mathbf{Q} \triangleq \left\{\mathbf{Q}_k^X:\ \forall k \in \mathcal{S}^X,\ X \in \{UL, DL\}\right\}$ and $\mathbf{\Upsilon} \triangleq \left\{\mathbf{\Upsilon}_i^X : \forall i \in \mathcal{S}^{RU},\ X \in \{UL, DL\}\right\}$ denote the set of all source and quantization noise covariance matrices, respectively.

Observing that the objective function (14a), and the fronthaul constraints (3) and (10) are in DC form, we can apply an iterative MM based algorithm, which solves a sequence of convex problems by linearizing the original non-convex functions in the optimization problem (14) at each iteration [7], [8].

To that end, by applying the first-order Taylor series approximation on the non-convex terms in the objective function and the constraints, at iteration $n+1$, the convex problem (15) given at the top of the following page is solved. In (15), the function $f(\mathbf{A}, \mathbf{B})$ is the first-order Taylor approximation of log-det function, and is given as

$$f(\mathbf{A}, \mathbf{B}) \triangleq \log|\mathbf{B}| + \frac{1}{\ln 2}\mathrm{tr}\left\{\mathbf{B}^{-1}\left(\mathbf{A} - \mathbf{B}\right)\right\}.$$

The steps of the proposed algorithm is illustrated in Algorithm 1.

$$
\begin{aligned}
\max_{\mathbf{Q}^{[n+1]},\boldsymbol{\Upsilon}^{[n+1]}} \quad & \sum_{k=1}^{K_{DL}} \left(\log\left|\mathbf{H}_k^{DL}\mathbf{Q}_k^{DL,[n+1]}\left(\mathbf{H}_k^{DL}\right)^H+\boldsymbol{\Sigma}_k^{DL,[n+1]}\right|-f\left(\boldsymbol{\Sigma}_k^{DL,[n+1]},\boldsymbol{\Sigma}_k^{DL,[n]}\right)\right) \\
& +\log\left|\sum_{k=1}^{K_{UL}}\mathbf{H}_k^{UL}\mathbf{Q}_k^{UL,[n+1]}\left(\mathbf{H}_k^{UL}\right)^H+\boldsymbol{\Sigma}^{UL,[n+1]}\right|-f\left(\boldsymbol{\Sigma}^{UL,[n+1]},\boldsymbol{\Sigma}^{UL,[n]}\right) && \text{(15a)}\\
\text{s.t.} \quad & f\left(\mathbf{E}_i^H\sum_{k=1}^{K_{DL}}\mathbf{Q}_k^{DL,[n+1]}\mathbf{E}_i+\boldsymbol{\Upsilon}_i^{DL,[n+1]},\mathbf{E}_i^H\sum_{k=1}^{K_{DL}}\mathbf{Q}_k^{DL,[n]}\mathbf{E}_i+\boldsymbol{\Upsilon}_i^{DL,[n]}\right)-\log\left|\boldsymbol{\Upsilon}_i^{DL,[n+1]}\right|\leq C_i^{DL},\ i\in\mathcal{S}^{RU} && \text{(15b)}\\
& f\left(\boldsymbol{\Phi}_i^{UL,[n+1]}+\boldsymbol{\Upsilon}_i^{UL,[n+1]},\boldsymbol{\Phi}_i^{UL,[n]}+\boldsymbol{\Upsilon}_i^{UL,[n]}\right)-\log\left|\boldsymbol{\Upsilon}_i^{UL,[n+1]}\right|\leq C_i^{UL}, i\in\mathcal{S}^{RU}, && \text{(15c)}\\
& \mathrm{tr}\left\{\mathbf{E}_i^H\sum_{k=1}^{K_{DL}}\mathbf{Q}_k^{DL,[n+1]}\mathbf{E}_i+\boldsymbol{\Upsilon}_i^{DL,[n+1]}\right\}\leq P_i^{DL},\ i\in\mathcal{S}^{RU}, \qquad \mathrm{tr}\left\{\mathbf{Q}_k^{UL,[n+1]}\right\}\leq P_k^{UL},\ k\in\mathcal{S}^{UL}, && \text{(15d)}\\
& \mathrm{tr}\left\{\tilde{\mathbf{H}}_l^{DL}\left(\sum_{k=1}^{K_{DL}}\mathbf{Q}_k^{DL,[n+1]}+\mathrm{diag}\left\{\boldsymbol{\Upsilon}_1^{DL,[n+1]},\ldots,\boldsymbol{\Upsilon}_{K_{RU}}^{DL,[n+1]}\right\}\right)\left(\tilde{\mathbf{H}}_l^{DL}\right)^H\right.\\
& \qquad\qquad \left.+\sum_{k=1}^{K_{UL}}\tilde{\mathbf{H}}_{lk}^{UL}\mathbf{Q}_k^{UL,[n+1]}\left(\tilde{\mathbf{H}}_{lk}^{UL}\right)^H\right\}\leq\lambda_l,\ l\in\mathcal{S}^{PU}, && \text{(15e)}\\
& \boldsymbol{\Upsilon}_i^{X,[n+1]}\succeq\mathbf{0},\ i\in\mathcal{S}^{RU},\ X\in\{UL,DL\}, \qquad \mathbf{Q}_k^{X,[n+1]}\succeq\mathbf{0},\ k\in\mathcal{S}^X,\ X\in\{UL,DL\}. && \text{(15f)}
\end{aligned}
$$

Algorithm 1 Sum-Rate Maximization Algorithm

1: Set the iteration number $n=1$ and initialize the source covariance $\mathbf{Q}^{[n]}$ and the quantization noise covariance matrices $\boldsymbol{\Upsilon}^{[n]}$.
2: **repeat**
3: Update $\mathbf{Q}^{[n+1]}$ and $\boldsymbol{\Upsilon}^{[n+1]}$ by solving the problem (15).
4: $n\leftarrow n+1$.
5: **until** convergence or maximum number of iterations is reached.
6: Calculate the precoding matrices $\mathbf{V}_k^X$ from the source covariance matrices $\mathbf{Q}_k^X$ via rank reduction method [10] as $\mathbf{V}_k^X=\lambda_k^X g\left(\mathbf{V}_k^X,d_k^X\right),\ \forall k\in\mathcal{S}^X,\ X\in\{UL,DL\}$, where the function $g\left(\mathbf{V},d\right)$ is a unitary matrix containing the d eigenvectors as columns corresponding to the largest d eigenvalues of the semi-positive definite matrix $\mathbf{V}$, and λ_k^X is the normalization factor computed from the power constraints.

Remarks:

1) Quality of Service (QoS) Constraint: In addition to the sum-rate maximization design in (14), we can also include a target rate for each UL/DL user as a constraint. The motivation behind this design is that even if FD outperforms HD in terms of total throughput, this does not guarantee that all UL/DL users are served evenly in every time slot. In some instances an UL user may achieve a lower rate in order to reduce the amount of interference present in the system. To that end, QoS-constrained optimization problem is reformulated as

$$
\begin{aligned}
\max_{\mathbf{Q},\boldsymbol{\Upsilon}} \quad & \sum_{k=1}^{K_{DL}} R_k^{DL}+R^{UL} && \text{(15a)}\\
\text{s.t.} \quad & (3),\ (4),\ (8),\ (10),\ (13),\ (14c),\ (14d) && \text{(15b)}\\
& R_k^{DL}\geq r^{DL},\ k=1,\ldots,K_{DL}, && \text{(15c)}\\
& R^{UL}\geq r^{UL}, && \text{(15d)}
\end{aligned}
$$

where r^{DL} and r^{UL} are the minimum data rates required by the DL and UL users, respectively. The key difficulty in solving the problem (15) is the rate constraints (15c) and (15d). However, we can use the local approximation used in (15a) to approximate these nonlinear and non-concave functions and then solve the problem (15) successively using MM, which we will not repeat due to space limitations.

2) Channel state information acquisition: It is challenging to obtain an accurate estimate for the channel state information (CSI) between the secondary and primary networks, as the primary network is usually not willing to cooperate with the secondary network [11]- [14]. In this regard, few methods have been suggested to combat this problem. Firstly, in case the primary system adopts the time-division-duplex (TDD) scheme, the secondary network can obtain the CSI to the primary nodes by taking advantage of the channel reciprocity, and overhearing the transmissions from the primary network [15]- [19]. Secondly, a partial CSI can be obtained via blind environmental learning [20], [21]. Third, an estimate of CSI can be obtained via the realization of a *band manager* with the ability to exchange the CSI between the secondary and primary networks [16], [17], [22], and finally, if possible, the primary and secondary networks can cooperate for the exchange of channel estimates [15]. Note that in the proposed algorithm, the transmit and receive filters are designed at a central scheduler design with the help of CSI feedbacks at the secondary network [18]

IV. Simulation Results

In this section, we compare the sum-rate performance of the proposed FD C-RAN scheme with that of the HD C-RAN scheme, under various system conditions. Unless otherwise stated, the following parameters are used in our simulations: $K_R=4$, $M_k=N_k=2,\ \forall k\in\mathcal{S}^{RU}$, $K_{DL}=K_{UL}=4$, $K_{PU}=1$ with $P_k=3,\ \forall k\in\mathcal{S}^{PU}$, and $T_k=R_k=2,\ \forall k$. Moreover, we assume that every RU and every UL user have the same power constraints, i.e, $P_i^{DL}=P^{DL}=26$dBm, $i\in\mathcal{S}^{RU}$ and $P_k^{UL}=P^{UL}=23$dBm, $k\in\mathcal{S}^{UL}$, and

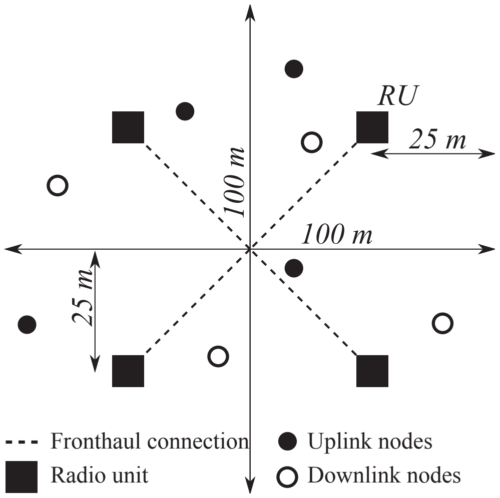

Fig. 2. The simulated setup. RUs are located at the center of each small square (50×50), where the position of the UL and DL users are chosen randomly.

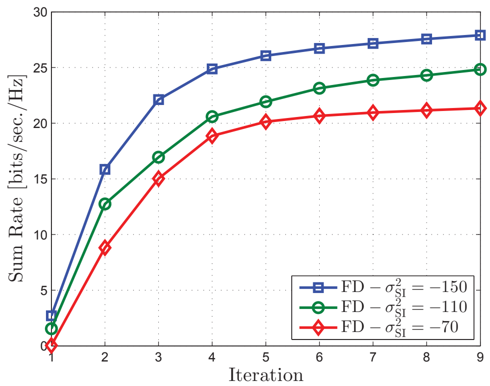

Fig. 3. Sum rate [bits/sec./Hz] vs. Algorithm iterations.

the noise powers in both UL and DL channels are equal $\sigma_{DL}^2 = \sigma_{UL}^2 = -107$dBm. The fronthaul constraints are assumed to be the same for all RUs in both UL and DL channels, i.e., $C_i^X = 10^7$bits/sec, $\forall i \in \mathcal{S}^{RU}$, $X \in \{UL, DL\}$, and the wireless system operates on the bandwidth of 10 MHz. The users are randomly located in a square area of side length 100m. Dividing this square into 4 equal small squares with a side length 50m, each of $K_R = 4$ RUs is located at the center of these 4 small squares, see Fig. 2. The position of the UL and DL users within each square area is chosen randomly for each channel realization. For the self-interference channel, we adopt the model in [1], in which the self-interference channel $\mathbf{H}_{ii}^{UD}$ at the ith RU is distributed as Rician with mean $\sqrt{\frac{\sigma_{SI}^2 \kappa}{1+\kappa}}$ and variance $\frac{\sigma_{SI}^2}{1+\kappa}$, where κ and σ_{SI}^2 represent the Rician factor and the residual self-interference power, respectively. The rest of the channel matrices follows a complex Gaussian distribution with path-loss defined as $\text{PL} = 22.9 + 37.5 \log_{10} d$ in dB where d is the distance in meters between relevant entities. Unlike the FD setup, where UL and DL users can be active simultaneously, a TDD scheme is considered for an equivalent HD setup to connect the UL and DL users in the subsequent time slots.

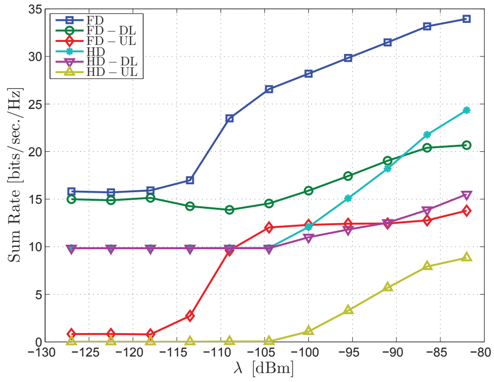

Fig. 4. Sum rate [bits/sec./Hz] vs. tolerable interference threshold at the PUs λ [dBm].

Due to the iterative nature, the convergence behavior of the proposed algorithm is of interest, both as a verification of the algorithm operation and as an indication of the computational complexity. In Fig. 3, the average convergence behavior of the algorithm is depicted. A monotonic increase is observed, where convergence is achieved in around 10 iterations.

In Fig. 4, the sum rate performance of the proposed FD C-RAN system is studied as a secondary system, co-existing with a primary network. It is observed that as the tolerable interference threshold decreases, the system sum rate degrades for both FD and HD scenarios. Moreover, it is observed that the sum rate of the DL users hold a higher level of robustness as the interference threshold decreases. In particular, a small value of λ results in a close-to-zero sum rate in UL users. This is perceivable, as the coordinated beamforming in the DL enables the arrangement of transmit beams in the null-space of interference channels to the PUs.

The impact of the residual self-interference intensity, i.e., σ_{SI}^2, is depicted in Fig. 5. It is observed that as the σ_{SI}^2 increases, the overall performance degrades. In particular, for a system with a large σ_{SI}^2, the co-existence of UL and DL is not feasible, due to the severe impact of the self-interference. This leads to a clear performance degradation as σ_{SI}^2 increases. On the other hand, for a system with a small σ_{SI}^2 and a large λ, a significantly higher performance is observed, due to the successful co-existence of DL and UL communications.

It is worth mentioning that due to the consideration of system sum rate as the evaluation metric, the FD system outperforms the HD setup for any residual self-interference, or interference threshold conditions. This stems from the fact that for any optimal HD network operation, the set of all UL or all DL communications can be exclusively enabled in the FD setup, resulting in a superior sum rate performance. Nevertheless, this leads to the unfair rate distribution among the UL and DL users[1] The fairness can be further improved by enabling the FD operation jointly with TDD capability [23], or by explicitly imposing the rate requirements as additional constraints.

[1]For instance, for a strong residual self-interference condition, a single directional communication can be established in the preferred direction, i.e., UL or DL, as a result of an optimized FD system design, following the sum rate maximization approach.

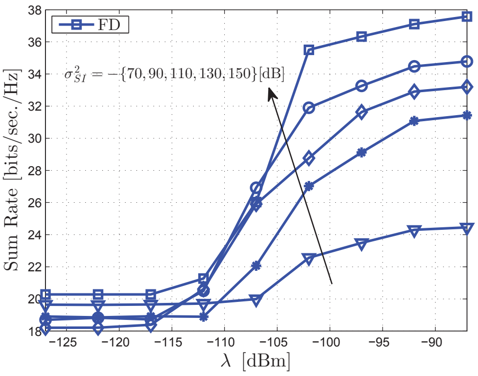

Fig. 5. The impact of the self-interference channel σ_{SI}^2 is depicted for different values of λ [dBm].

V. Conclusion

In this work, joint design of fronthaul compression and precoding in cloud radio access networks is studied for FD MIMO underlay cognitive radio networks. Combining the benefits of FD transmission at RUs with the FD fronthaul leads to efficient reuse of RAN spectrum, alleviates the need to obtain dedicated spectrum for fronthaul, and facilitates hardware implementation by enabling the use of same hardware for access links and fronthaul links. While the FD operation can ideally double the spectral efficiency in a link, the network-level gain of exploiting FD transmission in the fronthaul remains unclear due to the complicated interference environments, e.g., self-interference, co-channel interferences (CCI) at the fronthaul and access links. Numerical simulations verify a significant gain due to the additional coordinatioin among the radio units and the FD operation, in terms of the spectral efficiency, via the proposed design.

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