QoS Considerations for Full Duplex Multi-user MIMO Systems

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***Abstract*—We consider a full-duplex (FD) multi-user multiple-input multiple-output (MIMO) system where the base-station (BS) serves multiple uplink (UL) and downlink (DL) users simultaneously. We address the Quality-of-Service (QoS) problem, in which the transmitted sum-power at the BS and UL users is minimized subject to minimum rate constraints at each user of the system. We first propose a centralized solution based on sequential convex programming (SCP), and then propose a distributed solution by using interference prices exchanged among the nodes to represent the cost of received interference. The proposed designs are evaluated via numerical simulations.**

Keywords*—*Full-duplex, MIMO, multi-user, quality-of-service.

I. Introduction

In current wireless communication systems, downlink (DL) and uplink (UL) channels are designed to operate in 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. 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. Therefore, resource allocation problems for FD multi-user systems, where a FD capable base-station (BS) communicates with half-duplex (HD) UL and DL users, under the residual self-interference were considered in [1]-[5]. The authors in [1]-[3] have focused on the maximization of the achievable rate and have not addressed the issue of Quality-of-Service (QoS). However, in most practical cases, each user has a desired data rate and likes to achieve it within the available power. Thus, it is also an important problem to guarantee all the UL and DL users' desired data rates in a cellular system while consuming minimum power. Transmit power minimization is also important to extend battery life, which is desirable with battery-powered nodes [6]. In [4] and [5] , the authors study the QoS problem for UL and DL channels separately for single-antenna users, but the proposed algorithms do not provide a closed-form solution.

In this work, we propose a precoder scheme for the FD multiple-input multiple-output (MIMO) multi-user system to minimize the total transmitted power at the BS and UL users subject to a pre-determined data rate constraint at each user of this system as a QoS measure. We propose a centralized algorithm, where the non-convex optimization problem is approximated in each iteration with a known convex structure. We also propose a distributed algorithm, based on the exchange of interference prices among the nodes which represent the cost for the interference a node receives from other nodes. Our approach differs from the distributed algorithm in [7], which treats the multiple transmitter beams separately. Furthermore, unlike [4], [5] and [7], we provide a closed-form solution for the transmit covariance matrices which depends on the pricing values exchanged. Simulation results show the behavior of the proposed designs, in comparison with an equivalent HD system. It is observed that for both centralized and distributed designs, the FD solutions outperform the corresponding HD counter parts for the achievable values of self-interference cancellation quality.

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, $\mathrm{tr}(\cdot)$ is the trace, $|\cdot|$ is the determinant, and $\|\cdot\|_{\text{Fro}}$ is the Frobenius norm of a matrix. $\mathbb{C}^{M\times N}$ denotes the set of complex matrices with a dimension of $M\times N$, $(x)^+=\max\{x,0\}$, and $\otimes$ denotes the Kronecker product.

II. System Model

We consider a multi-user MIMO system, in which a FD BS equipped with M_0 and N_0 transmit and receive antennas serves K UL and J DL users simultaneously. The number of antennas at the k-th UL and the j-th DL user are M_k and N_j, respectively. $\mathbf{H}_k^{UL}\in\mathbb{C}^{N_0\times M_k}$ and $\mathbf{H}_j^{DL}\in\mathbb{C}^{N_j\times M_0}$ represent the k-th UL and the j-th DL channel, respectively. $\mathbf{H}_0\in\mathbb{C}^{N_0\times M_0}$ is the self-interference channel at the BS. $\mathbf{H}_{jk}^{DU}\in\mathbb{C}^{N_j\times M_k}$ denotes the co-channel interference (CCI) channel from the k-th UL user to the j-th DL user. [1]

The source symbols for the k-th UL and the j-th DL user are denoted as $\mathbf{s}_k^{UL}\in\mathbb{C}^{d_k^{UL}}$ and $\mathbf{s}_j^{DL}\in\mathbb{C}^{d_j^{DL}}$, respectively. It is assumed that the symbols are independent and identically distributed (i.i.d.) with unit power. Denoting the precoders for the data streams of the k-th UL and the j-th DL user as $\mathbf{V}_k^{UL}=\left[\mathbf{v}_{k,1}^{UL},\ldots,\mathbf{v}_{k,d_k^{UL}}^{UL}\right]\in\mathbb{C}^{M_k\times d_k^{UL}}$, and

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[1]We assume that the perfect channel state information (CSI) of the channels is available at the BS. All the channels can be estimated using hand-shaking and pilot symbols [5]. Since the pilot signal of a FD node is echoed back to itself, and the received power of this echoed-backed pilot signal is very high, the self-interference channel can be estimated with high accuracy.

$\mathbf{V}_j^{DL} = \left[\mathbf{v}_{j,1}^{DL}, \ldots, \mathbf{v}_{j,d_j^{DL}}^{DL}\right] \in \mathbb{C}^{M_0 \times d_j^{DL}}$, respectively, the signal received at the BS and j-th DL user is written as[2]

$$\mathbf{y}_0 = \sum_{k=1}^{K} \mathbf{H}_k^{UL} \mathbf{V}_k^{UL} \mathbf{s}_k^{UL} + \mathbf{H}_0 \sum_{j=1}^{J} \mathbf{V}_j^{DL} \mathbf{s}_j^{DL} + \mathbf{n}_0, \quad (1)$$

$$\mathbf{y}_j^{DL} = \mathbf{H}_j^{DL} \sum_{j=1}^{J} \mathbf{V}_j^{DL} \mathbf{s}_j^{DL} + \sum_{k=1}^{K} \mathbf{H}_{jk}^{DU} \mathbf{V}_k^{UL} \mathbf{s}_k^{UL} + \mathbf{n}_j^{DL}, \quad (2)$$

where $\mathbf{n}_0 \in \mathbb{C}^{N_0}$ and $\mathbf{n}_j^{DL} \in \mathbb{C}^{N_j}$ denote the additive Gaussian noise at the BS and the j-th DL user, respectively.

The received signals are processed by linear decoders, denoted as $\mathbf{U}_k^{UL} = \left[\mathbf{u}_{k,1}^{UL}, \ldots, \mathbf{u}_{k,d_k^{UL}}^{UL}\right] \in \mathbb{C}^{N_0 \times d_k^{UL}}$, and $\mathbf{U}_j^{DL} = \left[\mathbf{u}_{j,1}^{DL}, \ldots, \mathbf{u}_{j,d_j^{DL}}^{DL}\right] \in \mathbb{C}^{N_j \times d_j^{DL}}$ by the BS and the j-th DL user, respectively. Therefore, the estimate of the data streams of the k-th UL and the j-th DL user are given as $\hat{\mathbf{s}}_k^{UL} = \left(\mathbf{U}_k^{UL}\right)^H \mathbf{y}_0$ and $\hat{\mathbf{s}}_j^{DL} = \left(\mathbf{U}_j^{DL}\right)^H \mathbf{y}_j^{DL}$, respectively. Using these estimates, the SINR values of the m-th stream of the k-th user in the channel $X,\ X \in \{UL, DL\}$ is written as

$$\gamma_{k,m}^X = \frac{\left|\left(\mathbf{u}_{k,m}^X\right)^H \mathbf{H}_k^X \mathbf{v}_{k,m}^X\right|^2}{\left(\mathbf{u}_{k,m}^X\right)^H \mathbf{\Sigma}_k^X \mathbf{u}_{k,m}^X + \sum_{n \neq m}^{d_k^X} \left|\left(\mathbf{u}_{k,m}^X\right)^H \mathbf{H}_k^X \mathbf{v}_{k,n}^X\right|^2},$$

where $\mathbf{\Sigma}_k^{UL}$ is the covariance matrix of the interference-plus-noise terms at the k-th UL user, and is written as[3]

$$\mathbf{\Sigma}_k^{UL} = \sum_{j \neq k}^{K} \mathbf{H}_j^{UL} \mathbf{V}_j^{UL} \left(\mathbf{V}_j^{UL}\right)^H \left(\mathbf{H}_j^{UL}\right)^H + \sum_{j=1}^{J} \mathbf{H}_0 \mathbf{V}_j^{DL} \left(\mathbf{V}_j^{DL}\right)^H \mathbf{H}_0^H + \mathbf{I}_{N_0}. \quad (3)$$

The QoS based optimization problem is formulated as follows

$$\min_{\substack{\bar{\mathbf{v}}^{UL}, \bar{\mathbf{u}}^{UL} \\ \bar{\mathbf{v}}^{DL}, \bar{\mathbf{u}}^{DL}}} \quad \sum_{k=1}^{K} \sum_{m=1}^{d_k^{UL}} \left(\mathbf{v}_{k,m}^{UL}\right)^H \mathbf{v}_{k,m}^{UL} + \sum_{j=1}^{J} \sum_{m=1}^{d_j^{DL}} \left(\mathbf{v}_{j,m}^{DL}\right)^H \mathbf{v}_{j,m}^{DL} \quad (4)$$

$$\text{s.t.} \quad \sum_{m=1}^{d_k^{UL}} \log_2\left(1 + \gamma_{k,m}^{UL}\right) \geq R_k^{UL},\ k \in \mathcal{S}^{UL}, \quad (5)$$

$$\sum_{m=1}^{d_j^{DL}} \log_2\left(1 + \gamma_{j,m}^{DL}\right) \geq R_j^{DL},\ j \in \mathcal{S}^{DL}, \quad (6)$$

where $\bar{\mathbf{v}}^X\left(\bar{\mathbf{u}}^X\right) = \left\{\mathbf{v}_{k,m}^X\left(\mathbf{u}_{k,m}^X\right) : \forall\,(k,m)\right\},\quad X \in \{UL, DL\}$, and R_k^{UL} and R_j^{DL} are the desired rates at the k-th UL and j-th DL user in bits/second/Hz, respectively. We use $\mathcal{S}^{UL}$ and $\mathcal{S}^{DL}$ to represent the set of K UL and J DL channels, respectively. Before we solve QoS based optimization problem (4)-(6), we will first simplify the notations similar to [2] by combining UL and DL channels. Denoting

$$\mathbf{H}_{ij} = \begin{cases} \mathbf{H}_j^{UL},\ i \in \mathcal{S}^{UL},\ j \in \mathcal{S}^{UL}, \\ \mathbf{H}_0,\ \ i \in \mathcal{S}^{UL},\ j \in \mathcal{S}^{DL}, \\ \mathbf{H}_{ij}^{DU},\ i \in \mathcal{S}^{DL},\ j \in \mathcal{S}^{UL}, \\ \mathbf{H}_i^{DL},\ i \in \mathcal{S}^{DL},\ j \in \mathcal{S}^{DL}, \end{cases} \mathbf{n}_i = \begin{cases} \mathbf{n}_0, \quad i \in \mathcal{S}^{UL}, \\ \mathbf{n}_i^{DL},\ \ i \in \mathcal{S}^{DL}, \end{cases}$$

and referring to $\mathbf{V}_i^X$, $\mathbf{U}_i^X$, $\gamma_{i,m}^X$, $\mathbf{\Sigma}_i^X$, $d_i^X,\ X \in \{UL, DL\}$ as $\mathbf{V}_i$, $\mathbf{U}_i$, $\gamma_{i,m}$, $\mathbf{\Sigma}_i$, d_i, the SINR of the m-th stream in the i-th link, $i \in \mathcal{S} \triangleq \mathcal{S}^{UL} \bigcup \mathcal{S}^{DL}$ can be written as

$$\gamma_{i,m} = \frac{\left|\mathbf{u}_{i,m}^H \mathbf{H}_{ii} \mathbf{v}_{i,m}\right|^2}{\mathbf{u}_{i,m}^H \left(\mathbf{\Sigma}_i + \sum_{n \neq m}^{d_i} \mathbf{H}_{ii} \mathbf{v}_{i,n} \mathbf{v}_{i,n}^H \mathbf{H}_{ii}^H\right) \mathbf{u}_{i,m}}, \quad (7)$$

where $\mathbf{\Sigma}_i = \sum_{j \in \mathcal{S}, j \neq i} \mathbf{H}_{ij} \mathbf{V}_j \mathbf{V}_j^H \mathbf{H}_{ij}^H + \mathbf{I}$.

Using the simplified notations and the proposition in [8, Theorem 1], the problem (4)-(6) is formulated as follows

$$\min_{\bar{\mathbf{V}}} \quad \sum_{i \in \mathcal{S}} \text{tr}\left\{\mathbf{V}_i^H \mathbf{V}_i\right\} \quad (8)$$

$$\text{s.t.} \quad \underbrace{\log_2\left|\mathbf{I} + \mathbf{V}_i^H \mathbf{H}_{ii}^H \mathbf{\Sigma}_i^{-1} \mathbf{H}_{ii} \mathbf{V}_i\right|}_{I_i(\mathbf{V})} \geq R_i,\ i \in \mathcal{S}, \quad (9)$$

where $\bar{\mathbf{V}} = \{\mathbf{V}_i : i \in \mathcal{S}\}$ and R_i is the desired rate at the i-th user in bits/second/Hz.

III. Centralized Design

In this part, we propose a centralized design strategy to solve (8)-(9) to evaluate an optimal performance of the network, and to act as a comparison benchmark. In order to deal with the non-convex problem (8)-(9), we follow a sequential convex programming (SCP) [9], where the problem is approximated as a convex optimization problem in each iteration. The sequential problem in the ℓ-th iteration can be hence formulated as

$$\min_{\mathbf{V}_{i,\ell}} \quad \sum_{i \in \mathcal{S}} \text{tr}\left\{\mathbf{V}_{i,\ell} {\mathbf{V}_{i,\ell}}^H\right\} \quad (10)$$

$$\text{s.t.} \quad I_{i,\ell-1}(\mathbf{V}) + 2\text{Re}\Big\{\sum_{j \in \mathcal{S}} \text{tr}\Big(\left(\mathbf{V}_{j,\ell} - \mathbf{V}_{j,\ell-1}\right)^H \mathbf{\Gamma}_{i,j,\ell}\Big)\Big\} \leq R_i,\ \forall i \in \mathcal{S}, \quad (11)$$

$$\|\mathbf{V}_{j,\ell} - \mathbf{V}_{j,\ell-1}\|_{\text{Fro}} \leq \delta \cdot \|\mathbf{V}_{j,\ell-1}\|_{\text{Fro}}, \quad (12)$$

where (11) represents the first order Taylor series approximation of the rate constraints, and δ holds the extension in which the applied Taylor approximation is valid and will be set numerically. $\mathbf{\Gamma}_{i,j,\ell}$ is the conjugate gradient of the i-th rate

[2] The main purpose of precoding in the UL channel is to match the precoding matrix with the channel properties to increase the received signal power and also to some extent reduce the CCI on the DL users, thereby improving the signal-to-interference-plus-noise-ratio (SINR).

[3] The covariance matrix of the aggregate interference-plus-noise terms of the j-th DL user, $\mathbf{\Sigma}_j^{DL}$ can be written similarly, i.e., by changing $\mathbf{H}_j^{UL}$, $\mathbf{V}_j^{UL}$ and $\mathbf{H}_0$ with $\mathbf{H}_j^{DL}$, $\mathbf{V}_i^{DL},\ i \neq j$ and $\mathbf{H}_{jk}^{DU},\ k = 1, \ldots, K$, respectively.

function with respect to the j-th precoder, at iteration ℓ:

$$\mathbf{\Gamma}_{i,j,\ell} := \frac{\partial I_{i,\ell}}{\partial \mathbf{V}_{j,\ell}^*}\Big|_{\mathbf{V}_{i,\ell-1},\,\forall i\in\mathcal{S}} \tag{13}$$

$$= \begin{cases} \frac{1}{\ln(2)}\mathbf{H}_{ii}^H\mathbf{\Sigma}_{i,\ell-1}^{-1}\mathbf{A}_{i,\ell-1}^{-1}\mathbf{H}_{ii}\mathbf{V}_{i,\ell-1}, & i=j,\\ \frac{-1}{\ln(2)}\mathbf{H}_{ij}^H\left[\mathbf{\Sigma}_{i,\ell-1}^{-1} - \left(\mathbf{\Sigma}_{i,\ell-1} + \mathbf{H}_{ii}\mathbf{V}_{i,\ell-1}\mathbf{V}_{i,\ell-1}^H\mathbf{H}_{ii}^H\right)^{-1}\right] \\ \quad\times \mathbf{H}_{ij}\mathbf{V}_{j,\ell-1}, & i\neq j,\end{cases}$$

where $\mathbf{A}_{i,\ell} := \mathbf{I} + \mathbf{H}_{ii}\mathbf{V}_{i,\ell}\mathbf{V}_{i,\ell}^H\mathbf{H}_{ii}^H\mathbf{\Sigma}_{i,\ell}^{-1}$. The iterations of SCP continues until a local optimum point is achieved. While the proposed SCP solution does not guarantee the global optimality, the optimization process is repeated for multiple initial and feasible points to approach, with higher confidence, a globally optimal solution. Note that the Taylor series approximation holds with enough accuracy if the value of δ is chosen small enough such that the Taylor approximation remains valid within the feasible set of (10)-(12) [9].

IV. Distributed Design

Since the complexity of the centralized algorithm increases substantially with the increased number of users, it is important to implement a distributed algorithm which requires a limited amount of information exchange between the links.

Denoting $\mathbf{Q}_i \triangleq \mathbf{V}_i\mathbf{V}_i^H$ as the source covariance matrix of the i-th link, the problem (8)-(9) can be rewritten as

$$\min_{\mathbf{Q}_i\succeq\mathbf{0},\ i\in\mathcal{S}} \quad \sum_{i\in\mathcal{S}} \mathrm{tr}\left\{\mathbf{Q}_i\right\} \tag{14}$$

$$\text{s.t.} \quad \underbrace{\log_2\left|\mathbf{I} + \mathbf{H}_{ii}\mathbf{Q}_i\mathbf{H}_{ii}^H\mathbf{\Sigma}_i^{-1}\right|}_{I_i(\bar{\mathbf{Q}})} \geq R_i,\ i\in\mathcal{S}. \tag{15}$$

The Karush-Kuhn-Tucker (KKT) conditions associated with the problem (14)-(15) for the i-th link is given by

$$\frac{\partial\mathcal{L}\left(\bar{\mathbf{Q}},\bar{\mu},\bar{\mathbf{G}}\right)}{\partial\mathbf{Q}_i} = \mathbf{0},\ \mathrm{tr}\left\{\mathbf{G}_i\mathbf{Q}_i\right\}\geq 0,\ \mu_i\geq 0,\ \mathbf{G}_i\succeq 0, \tag{16}$$

$$\mu_i\left(\log_2\left|\mathbf{I} + \mathbf{H}_{ii}\mathbf{Q}_i\mathbf{H}_{ii}^H\mathbf{\Sigma}_i^{-1}\right| - R_i\right)\geq 0, \tag{17}$$

where μ_i and $\mathbf{G}_i$ are the Lagrange multipliers for the constraint given in (15) and semidefiniteness constraint of $\mathbf{Q}_i$, respectively. In (16) $\bar{\mu}$, $\bar{\mathbf{G}}$, and $\bar{\mathbf{Q}}$ are obtained by stacking μ_i, $\mathbf{G}_i$ and $\mathbf{Q}_i,\ i\in\mathcal{S}$, respectively. Here $\mathcal{L}\left(\bar{\mathbf{Q}},\bar{\mu},\bar{\mathbf{G}}\right)$ denotes the Lagrangian function, given as

$$\mathcal{L}\left(\bar{\mathbf{Q}},\bar{\mu},\bar{\mathbf{G}}\right) = \sum_{i\in\mathcal{S}}\mathrm{tr}\left\{\left(\mathbf{I}-\mathbf{G}_i\right)\mathbf{Q}_i\right\} + \sum_{i\in\mathcal{S}}\mu_i\left(R_i - I_i\left(\bar{\mathbf{Q}}\right)\right).$$

By taking the derivative of $\mathcal{L}\left(\bar{\mathbf{Q}},\bar{\mu},\bar{\mathbf{G}}\right)$ with respect to $\mathbf{Q}_i$ and then using the property $\frac{\partial\mathrm{tr}(\mathbf{AX})}{\partial\mathbf{X}} = \mathbf{A}^T$, we have

$$\frac{\partial\mathcal{L}\left(\bar{\mathbf{Q}},\bar{\mu},\bar{\mathbf{G}}\right)}{\partial\mathbf{Q}_i} = \frac{\partial}{\partial\mathbf{Q}_i}\mathrm{tr}\left\{\left(\mathbf{I} + \sum_{j\in\mathcal{S},j\neq i}\mu_j\mathbf{H}_{ji}^H\mathbf{\Pi}_j\mathbf{H}_{ji}\right)\mathbf{Q}_i\right\} - \frac{\partial}{\partial\mathbf{Q}_i}\mu_i I_i\left(\bar{\mathbf{Q}}\right) - \frac{\partial}{\partial\mathbf{Q}_i}\mathrm{tr}\left\{\mathbf{G}_i\mathbf{Q}_i\right\},$$

where the interference sensitivity matrix, $\mathbf{\Pi}_j$ is defined as

$$\mathbf{\Pi}_j = \log_2 e\left(\mathbf{\Sigma}_j^{-1} - \left(\mathbf{H}_{jj}\mathbf{Q}_j\mathbf{H}_{jj}^H + \mathbf{\Sigma}_j\right)^{-1}\right). \tag{18}$$

Since the KKT conditions corresponding to the i-th link are coupled with all other links, which increases the difficulty of the problem, a distributed algorithm is proposed, in which the source covariance matrix of each link is optimized under the assumption that the interference sensitivity matrices, and the source covariance matrix of all other links are fixed. Under this assumption, the KKT conditions in (16)-(17), are actually the same as the KKT conditions of the following problem:

$$\min_{\mathbf{Q}_i\succeq\mathbf{0}} \quad \mathrm{tr}\left\{\mathbf{B}_i\mathbf{Q}_i\right\} \tag{19}$$

$$\text{s.t.} \quad \log_2\left|\mathbf{I} + \mathbf{H}_{ii}\mathbf{Q}_i\mathbf{H}_{ii}^H\mathbf{\Sigma}_i^{-1}\right| \geq R_i, \tag{20}$$

where $\mathbf{B}_i = \mathbf{I} + \sum_{j\in\mathcal{S},j\neq i}\mu_j\mathbf{H}_{ji}^H\mathbf{\Pi}_j\mathbf{H}_{ji}$ is the pricing matrix reflecting the compensation paid for the interference generated to other links. Note that unlike the global CSI assumption in the centralized method, in the distributed algorithm, to obtain $\mathbf{B}_i$, CSI must be only *locally* available at the transmitters, i.e., each transmitter needs to know only the CSI of the links originating from itself. The receiver at each link is able to obtain $\mathbf{\Sigma}_i$ locally through measurements [3].

The optimization problem (19)-(20) is a convex problem, which can be solved separately for each link, provided that the other links send the Lagrange multiplier for the rate constraint μ_j and the interference sensitivity matrices $\mathbf{\Pi}_j$. As the value of μ_i acts as the penalty weight regarding the corresponding rate constraint, it can be intuitively chosen as

$$\mu_i = \left[\left(R_i - I_i\left(\bar{\mathbf{Q}}\right)\right)/R_i\right]^+,\ \forall i\in\mathcal{S}, \tag{21}$$

which indicates that only paths with unsatisfied rate constraint will contribute to interference pricing term, proportional to the corresponding rate deficiency.

To solve (19)-(20), we first define the following matrix

$$\tilde{\mathbf{Q}}_i = \mathbf{U}_i^H\mathbf{B}_i^{1/2}\mathbf{Q}_i\mathbf{B}_i^{1/2}\mathbf{U}_i, \tag{22}$$

where $\mathbf{U}_i$ is a unitary matrix obtained by the eigenvalue decomposition of

$$\mathbf{B}_i^{-1/2}\mathbf{H}_{ii}^H\mathbf{\Sigma}_i^{-1}\mathbf{H}_{ii}\mathbf{B}_i^{-1/2} = \mathbf{U}_i\mathbf{\Lambda}_i\mathbf{U}_i^H. \tag{23}$$

In (23), $\mathbf{\Lambda}_i$ is a diagonal matrix containing the corresponding eigenvalues, $\lambda_{i,m},\ m = 1,\ldots,M$, and M is the number of antennas of the transmitter in the i-th link. Since $\mathbf{U}_i$ is a unitary matrix, from (22) we can write $\mathbf{Q}_i$ as

$$\mathbf{Q}_i = \mathbf{B}_i^{-1/2}\mathbf{U}_i\tilde{\mathbf{Q}}_i\mathbf{U}_i^H\mathbf{B}_i^{-1/2}. \tag{24}$$

By plugging (24) into the objective function (19), we have

$$\mathrm{tr}\left\{\mathbf{B}_i\mathbf{Q}_i\right\} = \mathrm{tr}\left\{\tilde{\mathbf{Q}}_i\right\}. \tag{25}$$

Moreover, plugging (24) into the data rate constraint in (20), and then using (23) in the resulting equation, we get

$$\log_2\left|\mathbf{I} + \mathbf{Q}_i\mathbf{H}_{ii}^H\mathbf{\Sigma}_i^{-1}\mathbf{H}_{ii}\right| = \log_2\left|\mathbf{I} + \tilde{\mathbf{Q}}_i\mathbf{\Lambda}_i\right|.$$

To maximize the determinant $\log_2\left|\mathbf{I}+\tilde{\mathbf{Q}}_i\mathbf{\Lambda}_i\right|$, from the Hadamard inequality, $\tilde{\mathbf{Q}}_i$ must be diagonal [10]. Thus, the problem (19)-(20) reduces to the following problem

$$\min_{\tilde{q}_{i,m}\geq 0,\ \forall i,m} \sum_{m=1}^{M} \tilde{q}_{i,m} \quad \text{s.t.} \sum_{m=1}^{M} \log_2\left(1+\tilde{q}_{i,m}\lambda_{i,m}\right) \geq R_i, \quad (26)$$

where $\tilde{q}_{i,m},\ m=1,\ldots,M$ is the m-th diagonal element of $\tilde{\mathbf{Q}}_i$. The solution of the problem (26) is written as

$$\tilde{q}_{i,m} = \left(\nu_i - \frac{1}{\lambda_{i,m}}\right)^{+}, \quad (27)$$

where ν_i is the water level adjusted to satisfy the user rate constraint (26). Once $\tilde{\mathbf{Q}}_i$ is computed using (27), the source covariance matrix, $\mathbf{Q}_i$ can be computed from (24).

Note that in the distributed method, both computation task and the network data exchange load is distributed. This becomes an important factor when network size grows.

V. Simulation Results

In this section, the consumed network power is depicted for the proposed centralized (SCP) and the distributed (Dist) methods under the 3GPP LTE specifications for small cell deployments [11]. A single hexagonal cell having a BS in the center with randomly distributed UL and DL users is simulated. The parameters for the system model and the path-loss model for each link are adopted from [11]. Please see [11, Table 6.2-1] for the detailed simulation parameters.

For the self-interference channel, we adopt the model in [12], which demonstrates that the Rician probability distribution with a small Rician factor should be used to characterize the residual self-interference channel after self-interference cancellation mechanisms. In this regard, the self-interference channel is distributed as $\mathbf{H}_0 \sim \mathcal{CN}\left(\sqrt{\frac{\sigma_{SI}^2 K_R}{1+K_R}}\tilde{\mathbf{H}}_0, \frac{\sigma_{SI}^2}{1+K_R}\mathbf{I}_{N_0}\otimes\mathbf{I}_{M_0}\right)$, where K_R is the Rician factor, $\tilde{\mathbf{H}}_0$ is a deterministic matrix, and σ_{SI}^2 is introduced to parametrize the capability of a certain self-interference cancellation design. The resulting system performance is averaged over 200 full-rank channel realizations. We apply the following values as our default system parameters: $\sigma_{SI}^2 = -100\text{dB},\ K_R = 1,\ M_k = N_j = d_i^{UL} = 2,\ M_0 = N_0 = d_i^{DL} = 2,\ K = J = 2$, and $\tilde{\mathbf{H}}_0$ is a matrix of all ones.

In Fig. 1, it is observed that the system power consumption is increased for the higher rate requirements, and the HD setup is outperformed by the FD setup for both centralized and distributed solutions. Moreover, since the self-interference power is weaker compared to the CCI power on the average, the DL channel consumes more power than the UL channel to achieve the same data rate constraint.

VI. Conclusion

We have proposed a centralized and a distributed algorithm for the QoS problem in a cellular FD MIMO system. It is shown that FD system consumes less power than the HD system under achieved self-interference cancellation levels for both centralized and distributed algorithms.

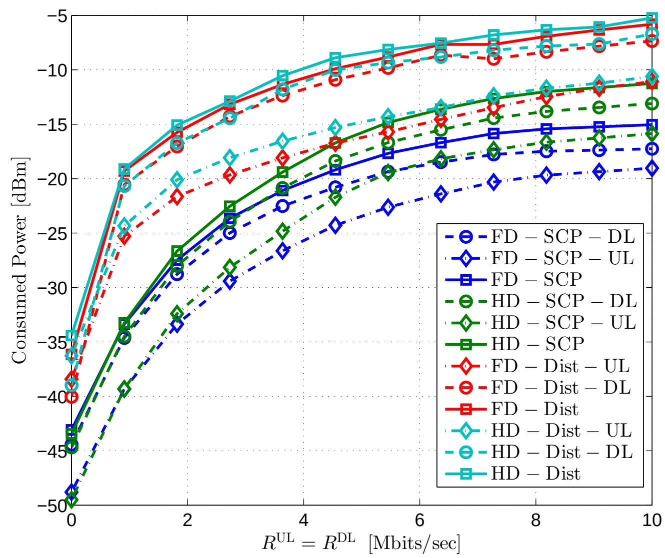

Fig. 1. Consumed power [dBm] vs. Required rate [Mbps].

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