D2D CSI Feedback for D2D Aided Massive MIMO Communications

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***Abstract*—We consider fast fading massive MIMO systems in Frequency Division Duplex (FDD) mode and propose a communication scheme based on Device-to-Device (D2D) cooperation and statistical channel state information (CSI) feedback. User terminals (UT) are conveniently clustered and cooperate within a cluster to create a virtual MIMO at a target UT via D2D communications. We propose and analyse the use of D2D CSI at a massive MIMO base station (BS) to enhance performance compared to statistical precoders oblivious of the underlying relaying links. In the case of uniform linear array (ULA) at the BS and slow fading channels for D2D links, the structure of an optimal precoder is characterized and an algorithm for optimal power allocation is proposed. The average sum rate of the proposed communication scheme is analyzed by numerical simulations and it is compared to a baseline protocol oblivious of the relaying CSI.**

I. Introduction

Thanks to a very large number of antennas at the base station, massive MIMO systems [1], [2] have impressive potentials to combat interference and enable high date rates [3]. Thus, they are widely considered fundamental building blocks of future 5G networks. CSI acquisition plays a fundamental role to enable interference-free communications in downlink and results especially challenging in FDD communications. When uplink-downlink channel reciprocity holds, standard techniques allow the acquisition of the downlink CSI at a cost that scales linearly with the number of users. In contrast, in FDD mode where reciprocity does not hold, the channel is estimated at the user terminals and each terminal needs to feedback an amount of information proportional to M, the number of transmit antennas. When the number of antennas is large as in massive MIMO, CSI acquisition becomes too costly or even impossible in practical systems with fading channels.

The challenge of reducing CSI acquisition costs in FDD massive MIMO system spurred several recent works [4]–[8]. A substantial reduction of feedback can be obtained by leveraging on the reduced rank of the user channel covariance matrix in massive MIMO systems [6], [9], [10] as proposed in the Joint Spatial Division and Multiplexing (JSDM) protocol [4], [5]. The key idea of the JSDM protocol consists in clustering users whose effective channel subspaces (ECS), i.e. the channel covariance matrix images, are ideally identical and in practice substantially overlapping. Transmissions to clusters with orthogonal ECSs can be scheduled simultaneously: Statistical beamformers that project the cluster signals onto their respective ECSs can guarantee interference free communications among clusters. Intra-cluster interference is mitigated or annihilated by precoders based on the known ECSs. To design the precoders, the feedback of the CSI in the ECS basis suffices. As result, the feedback cost is proportional to the ECS dimension. Although substantially reduced compared to the feedback of the full dimensional CSI, this instantaneous feedback can be still too costly in practical systems. Since heterogeneity is expected to be an intrinsic property of 5G networks, in [11]–[13] we benefit from synergies between D2D communication systems and massive MIMO networks to further reduce feedback. In [11], D2D cooperation is utilised to reconstruct global instantaneous CSI at the user terminals such that the optimum instantaneous feedback can be designed. In [12], [13], we completely avoid instantaneous feedback by creating virtual MIMOs (V-MIMO) within users in the same cluster. More specifically, in [12], [13] at each channel use and for each cluster of n users, b information data streams for a target user in a given cluster are precoded and subsequently beamformed for transmission. Each non-target user in the cluster amplifies and forwards the received signal such that the target user receives $n-1$ additional independent versions of the transmit signal to create a V-MIMO system. The communication scheme in [12], [13], dubbed shortly *D2D-oblivious virtual MIMO*, relies only on the statistics of the links between BS and user terminals (UT). A single precoder for each cluster is designed based on the knowledge of the statistical information about BS and UTs in a cluster. The BS is oblivious of the statistical CSI of the relaying links in a cluster. It assumes that the target user is a multi-antenna user with all the antennas collocated and the channel statistics coinciding with the ones of the downlink channel. In this paper, we modify the communication scheme requiring the feedback of the CSI of the D2D links. Then, this protocol, referred to as *D2D-aware virtual MIMO*, assumes that the BS has knowledge of the statistical CSI of each V-MIMO such that the base station can optimally design a precoding matrix for each V-MIMO.

The optimal design of precoders for point-to-point MIMO systems with only statistical channel knowledge at the transmitter has been object of intensive studies in the previous decade and the most general results, up to the author's knowledge are presented in [14], [15] for the so called Kronecker channel model and have been utilised in [13]. However, in the D2D-aware V-MIMO scheme, the relay phase based on amplify-and-forward modifies substantially the statistical properties of the equivalent V-MIMO channel model and the results in [14] are not applicable. In the case of ULA at the base station, we show that an optimal statistical precoder for V-MIMO has a diagonal structure and we derive an algorithm for the optimal precoding design. This optimal precoder is utilized to assess the performance of the D2D-aware V-MIMO scheme. Its performance is compared to the D2D-oblivious V-MIMO scheme adopted as baseline.

The following notation has been used throughout the paper: Boldface uppercase and lowercase letters denote matrices and vectors, respectively. Scalars are in italic. $\mathbf{I}_n$ is the identity matrix of size $n \times n$ and $\mathbf{1}_n$ is the n-dimensional vector of ones. The Hermitian operator of a matrix $\mathbf{X}$ is denoted by $\mathbf{X}^H$. $\mathcal{CN}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$ denotes a complex Gaussian random vector with mean $\boldsymbol{\mu}$ and covariance $\boldsymbol{\Sigma}$. $\mathbb{E}\{\cdot\}$ is the expectation operator; $\mathrm{tr}(\cdot)$ denotes the trace of the matrix argument. Finally, $\mathrm{diag}(\mathbf{v})$ is the square diagonal matrix having the element of vector $\mathbf{v}$ as diagonal elements.

II. System Model

Throughout this paper we adopt the same system model and notation as in [13]. To keep the paper self-contained the system model is shortly described in this section. A BS endowed with a very large antenna array of M antennas serves single antenna users. The downlink channel is fast fading and non-reciprocal. The covariance matrix $\mathbf{R}_k$ of the zero mean user k channel is known at the BS. The channel presents the reduced rank properties pointed out in [9], [10], [16] such that ECSs –the image of $\mathbf{R}_k$ – have substantially lower dimension than M. Then, the JSDM protocol in [16] can be applied and users with almost completely overlapping ECS are in cluster $\mathcal{C}$. To each cluster $\mathcal{C}$ we can associate a cluster covariance matrix $\mathbf{R}_c$ obtained as average of the single users channel covariances. The subspace spanned by the image of $\mathbf{R}_c$ is called the cluster ECS. To simplify system model and analytical tractability of the problem we assume strict orthogonality of the cluster ECSs. In this case, the cluster signals do not interfere with simultaneous transmissions in other clusters. Thus, in the following we can focus on a single cluster with n users.

The communication system from the BS to the users in cluster $\mathcal{C}$ is given by

$$\mathbf{y} = \mathbf{H}_c^H \mathbf{B}\mathbf{s} + \mathbf{n}, \tag{1}$$

where $\mathbf{y}$ is the n-dimensional complex column vector of received signals at all the cluster users; $\mathbf{s}$ denotes the vector of i.i.d. Gaussian signals with zero-mean and unit-variance; and $\mathbf{n}$ represents the spatially and temporally white additive Gaussian noise (AWGN) with zero-mean and element-wise variance σ_n^2. Finally, $\mathbf{B}$ is the down-link beamformer such that $\mathrm{tr}\{\mathbf{B}\mathbf{B}^H\} = P_{max}$, where P_{max} is the total transmit power constraint. The downlink channel between the BS and the k-th user in the cluster $\mathcal{C}$ is denoted by the M-dimensional complex vector $\mathbf{h}_k$. Therefore,

$$\mathbf{H}_c = [\mathbf{h}_1, \mathbf{h}_2, \dots \mathbf{h}_n] \in \mathbb{C}^{M \times n} \tag{2}$$

and $\mathbf{R}_k = \mathbb{E}\{\mathbf{h}_k \mathbf{h}_k^H\}$. Assuming that the $\mathbf{R}_c$, the cluster covariance matrix has rank b with $b < M$ we can decompose it as

$$\mathbf{R}_c = \widetilde{\mathbf{U}} \widetilde{\boldsymbol{\Lambda}} \widetilde{\mathbf{U}}^H \tag{3}$$

where $\widetilde{\boldsymbol{\Lambda}}$ is the $b \times b$ matrix of the nonzero eigenvalues of $\mathbf{R}_c$ in non increasing order and $\widetilde{\mathbf{U}}$ is the $M \times b$ matrix whose columns are the normalized eigenvectors of $\mathbf{R}_c$. Similarly, $\mathbf{R}_k = \widetilde{\mathbf{U}}_k \widetilde{\boldsymbol{\Lambda}}_k \widetilde{\mathbf{U}}_k^H$, with analogous meaning for b_k, $\widetilde{\boldsymbol{\Lambda}}_k$ and $\widetilde{\mathbf{U}}_k$. Since, by construction, the subspace spanned by the column vectors of $\widetilde{\mathbf{U}}_k$ lies into the subspace spanned by the column vectors of $\widetilde{\mathbf{U}}$, then $\widetilde{\mathbf{U}}_k = \widetilde{\mathbf{U}}\mathbf{T}_k$, where $\mathbf{T}_k$ is a $b \times b$ matrix whose i-th column elements are the coefficients of the i-th column of $\widetilde{\mathbf{U}}_k$ in the basis $\widetilde{\mathbf{U}}$. Additionally, the Gaussian vector $\mathbf{h}_k$ can be expressed as $\mathbf{h}_k = \widetilde{\mathbf{U}}_k \widetilde{\boldsymbol{\Lambda}}_k^{1/2} \widetilde{\mathbf{h}}_k$ being $\widetilde{\mathbf{h}}_k$ a b_k-dimensional vector of zero-mean, unit variance, independent Gaussian elements. Then,

$$\mathbf{H}_c = \widetilde{\mathbf{U}} \left[\mathbf{T}_1 \widetilde{\boldsymbol{\Lambda}}_1^{1/2} \widetilde{\mathbf{h}}_1, \cdots \mathbf{T}_n \widetilde{\boldsymbol{\Lambda}}_n^{1/2} \widetilde{\mathbf{h}}_n \right] = \widetilde{\mathbf{U}} \mathbf{A}_c, \tag{4}$$

where $\mathbf{A}_c$ is a matrix of Gaussian elements, in general, column-wise correlated. In the following we adopt the notation $\mathbf{a}_{ck} = \mathbf{T}_k \widetilde{\boldsymbol{\Lambda}}_k^{1/2} \widetilde{\mathbf{h}}_k$.

Finally, the projection of the precoded signals onto the cluster ECS $\widetilde{\mathbf{U}}$ yields the equivalent system model

$$\mathbf{y} = \mathbf{A}_c^H \widetilde{\mathbf{B}} \mathbf{s} + \mathbf{n}. \tag{5}$$

Here, $\widetilde{\mathbf{B}}$ is the precoder in the cluster ECS satisfying the relation $\mathbf{B} = \widetilde{\mathbf{U}}\widetilde{\mathbf{B}}$ and $\widetilde{\mathbf{U}}$ the projection beamformer.

The received signal at user k is given by

$$y_k = \mathbf{a}_{ck}^H \widetilde{\mathbf{B}} \mathbf{s} + \mathbf{n} \tag{6}$$

and the corresponding averaged received power is

$$P_k = \mathrm{tr}\{\mathbf{B}^H \mathbf{R}_k \mathbf{B}\} + \sigma_n^2. \tag{7}$$

The users in $\mathcal{C}$ create a virtual MIMO by retransmitting the received signals in orthogonal time intervals. User ℓ amplifies and forwards its received signal y_ℓ such that its transmitted signal is

$$x_\ell = \sqrt{\frac{P_r}{P_\ell}} y_\ell$$

P_r being the average transmit power constraint as user ℓ acts as relay.

Motivated by physical considerations and supported by the analysis in [10], users within a cluster are closely located and far apart from users in other clusters. Then, we can assume that the simultaneous D2D transmissions do not interfere each other. Thus, the signal received by user k from user ℓ is given by

$$\begin{aligned} r_k &= g_{k\ell} x_\ell + w_k \\ &= \sqrt{\frac{P_r}{P_\ell}} g_{k,\ell} \mathbf{a}_{ck}^H \widetilde{\mathbf{B}}^H \mathbf{s} + \sqrt{\frac{P_r}{P_\ell}} g_{k\ell} n_\ell + w_k \end{aligned} \tag{8}$$

where $g_{k,\ell}$ is the channel coefficient of the fading link from user ℓ to user k, realization of a Gaussian random process with variance $\gamma_{k,\ell}$. Finally, w_k is the additive Gaussian noise with variance σ_r^2 at user k when it acts as receiver in the D2D communications.

At the end of the relaying phase, user k has n independent received versions of the original transmitted signal and can act as a V-MIMO. The corresponding system model is given by

$$\mathbf{r}_k = \boldsymbol{\Gamma}_k \mathbf{A}_c^H \widetilde{\mathbf{B}} \mathbf{s} + \mathbf{z}_k \tag{9}$$

where $\boldsymbol{\Gamma}_k$ is an $n \times n$ diagonal matrix with j-th diagonal elements given by

$$(\boldsymbol{\Gamma}_k)_{jj} = \begin{cases} \sqrt{\dfrac{P_r}{P_j}} g_{k,j}, & \text{if } j \neq k; \\ 1, & \text{if } j = k \end{cases} \tag{10}$$

and $\mathbf{z}_k$ is the equivalent Gaussian noise with diagonal covariance matrix $\boldsymbol{\Sigma}_k$. The diagonal elements of $\boldsymbol{\Sigma}_k$ are defined by

$$(\boldsymbol{\Sigma}_k)_{jj} = \begin{cases} \dfrac{P_r}{P_j}\chi_{k,j}\sigma_n^2 + \sigma_r^2, & \text{if } j \neq k; \\ \sigma_n^2, & \text{if } j = k \end{cases} \tag{11}$$

with $\chi_{k,j} = |g_{k,j}|^2$ if the D2D links between UT j and UT k is slow fading and and $\chi_{k,j} = \gamma_{k,j}$ in the case of fast fading.

Throughout this paper, we focus on uniform linear array (ULA) and assume that the eigen-bases of all the user channel covariance matrices $\mathbf{R}_k$ are well approximated by a Fourier matrix [4], [9]. Under this assumption, it is easy to verify that the elements of the matrix $\mathbf{A}_c$ are independent and the variances of its entries can be assembled into the matrix

$$\mathbf{G} = \left(\mathrm{E}\{|a_{c,ij}|^2\}\right)_{\substack{i=1,\dots,b \\ j=1,\dots n}} = \left[\widetilde{\boldsymbol{\lambda}}_1, \widetilde{\boldsymbol{\lambda}}_2, \dots, \widetilde{\boldsymbol{\lambda}}_n\right] \tag{12}$$

where $\widetilde{\boldsymbol{\lambda}}_j$ is the diagonal of the matrix $\widetilde{\boldsymbol{\Lambda}}_j$, i.e. $\widetilde{\boldsymbol{\lambda}}_j = \mathrm{diag}\widetilde{\boldsymbol{\Lambda}}_j$.

III. D2D-Aware V-MIMO Communications

In the D2D-aware V-MIMO communication scheme, in the preamble phase each UT feeds back to the BS (a) the statistics of the links with neighbor users; (b) its transmit power level P_r as D2D transmitter; (c) the variance of the noise σ_r^2 as D2D receiver. Then, the base station designs a precoder for each V-MIMO channel taking into account the colored noise at the V-MIMO receiver and the V-MIMO channel statistics. Note that we can consider the equivalent channel model

$$\widetilde{\mathbf{r}}_k = \boldsymbol{\Sigma}_k^{-1/2}\boldsymbol{\Gamma}_k\mathbf{A}_c^H\widetilde{\mathbf{B}}\mathbf{s} + \widetilde{\mathbf{z}}_k \tag{13}$$

where $\widetilde{\mathbf{z}}_k$ is the additive white Gaussian noise at the D2D-receiver of user k. Let us consider the equivalent channel

$$\widetilde{\mathbf{H}}_k = \boldsymbol{\Sigma}_k^{-1/2}\boldsymbol{\Gamma}_k\mathbf{A}_c^H = \boldsymbol{\Xi}_k(\mathbf{Q}_k)^{-1}\mathbf{A}_c^H \tag{14}$$

being

$$\boldsymbol{\Xi}_k(\mathbf{Q}_k) = \mathbf{D}_k\mathbf{T}(\mathbf{Q}_k) + \mathbf{F}_k \tag{15}$$

and $\mathbf{D}_k$, $\mathbf{F}_k$ diagonal matrices with the j-th diagonal element defined by

$$d_{kj} = \begin{cases} \frac{\sigma_r^2}{P_r|g_{kj}|^2}, & j \neq k \\ 0, & j = k; \end{cases}$$

$$f_{kj} = \begin{cases} \sigma_n^2 + \frac{\sigma_r^2\sigma_n^2}{P_r\chi_{kj}}, & j \neq k \\ \sigma_n^2, & j = k; \end{cases}$$

and $\mathbf{T}(\mathbf{Q}_k) = \sum_{r=1}^{b} q_{k,r}\boldsymbol{\Lambda}^{(r)}$. Finally, $\boldsymbol{\Lambda}^{(r)}$ is the diagonal matrix with diagonal element $\Lambda_{jj}^{(r)} = \mathbb{E}(|a_{c,rj}|^2)$, i.e. the rth diagonal element of the matrix $\widetilde{\boldsymbol{\Lambda}}_j$.

In this section, we focus on the case of optimal design of the precoder $\widetilde{\mathbf{B}}$ under the assumption of ULA at the BS and statistical knowledge of the channel $\mathbf{A}_c$. Then, the elements of the matrix $\mathbf{A}_c$ are independent. However, the pre-multiplication by the diagonal matrices $\boldsymbol{\Xi}_k(\mathbf{Q}_k)$ may substantially change the statistical properties of the channel $\widetilde{\mathbf{H}}_k$. Additionally, $\boldsymbol{\Xi}_k(\mathbf{Q}_k)$ depends implicitly from the beamformer $\widetilde{\mathbf{B}}$ selected for transmission via the average received powers at the downlink receivers $P_1, P_2, \dots, P_n$ as defined in (7).

We can consider the following two cases. If the D2D links are slow fading and they are constant during a codeword transmission, then the columns of the matrix $\widetilde{\mathbf{H}}_k$ are independent for any choice of the matrix $\widetilde{\mathbf{B}}$. In contrast, they are statistically dependent if the D2D links are fast fading.

We focus on the first case corresponding to the practical situation when the UTs in a cluster are closely located and in line of sight. For such a case we optimize the precoding matrix $\mathbf{Q}_k$ to maximize the achievable rate at the virtual MIMO with user k as target user under a total average power constraint $\mathrm{tr}\mathbf{Q}_k = P_{\mathrm{MAX}}$, i.e.

$$\text{P1} \qquad \begin{array}{ll} \text{maximize} & \mathcal{I}(\mathbf{Q}_k) \\ \text{subject to} & \mathrm{tr}\mathbf{Q} = P_{\mathrm{MAX}} \end{array}$$

with

$$\mathcal{I}(\mathbf{Q}_k) = \mathbb{E}\log\det\left(\mathbf{I} + \boldsymbol{\Xi}_k^{-1}(\mathbf{Q}_k)\mathbf{A}_c^H\mathbf{Q}_k\mathbf{A}_c\right). \tag{16}$$

The optimization problem P1 does not reduce to the previously studied optimization problems for point-to-point MIMO systems in [14], [15] due to the matrix factor $\boldsymbol{\Xi}_k^{-1}(\mathbf{Q}_k)$. In the following we determine the optimal precoder. First of all we characterize the optimal precoder structure in the following proposition.

Proposition 1 *If the rows of the matrix $\mathbf{A}_c$ are zero mean independent and rotationally invariant and the matrix $\boldsymbol{\Xi}_k(\mathbf{Q}_k)$ is defined as in (15), then the capacity achieving input covariance matrix $\mathbf{Q}$ is diagonal.*

Due to space constraints the proof of this proposition is omitted but we acknowledge the use of an effective technique introduced in [17].

By invoking Proposition 1, we solve the optimization problem P1 assuming a diagonal matrix $\mathbf{Q}_k$. The solution to problem P1 shall satisfy the KKT conditions. However, in contrast to the point-to-point MIMO case where the KKT conditions are necessary and sufficient thanks to the convexity of the problem, for the V-MIMO systems the KKT conditions are only necessary.

Proposition 2 *Under the same assumptions of Proposition 1, the elements of the optimal diagonal matrix $\mathbf{Q}_k^*$ solution of P1 satisfy conditions (17) at the top of the following page with*

$$\mathcal{T}_m(\mathbf{Q}_k) = \mathrm{tr}[(\mathbf{A}_c^H\mathbf{Q}_k\mathbf{A}_c + \boldsymbol{\Xi}(\mathbf{Q}_k))^{-1}(\mathfrak{a}_m\mathfrak{a}_m^H + \mathbf{D}_k\boldsymbol{\Lambda}^{(m)})] \tag{18}$$

and $\mathfrak{a}_m$ denotes the mth column of the matrix $\mathbf{A}_c^H$ of dimension n different from the previously defined vectors $\mathbf{a}_{cr}$.

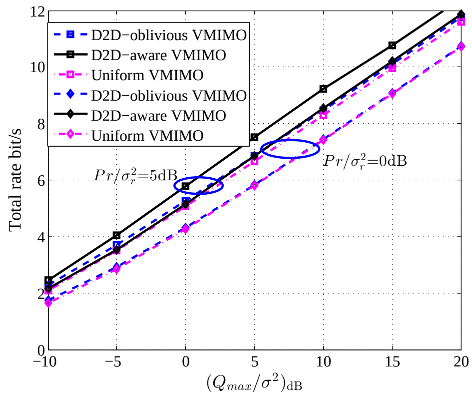
An algorithm to determine a matrix $\mathbf{Q}^*$ satisfying conditions (17) is reported below. Note that its convergence to the global optimum precoder is not guaranteed in contrast to the results for point-to-point MIMO in [15] and it is left for future study.

Algorithm 1

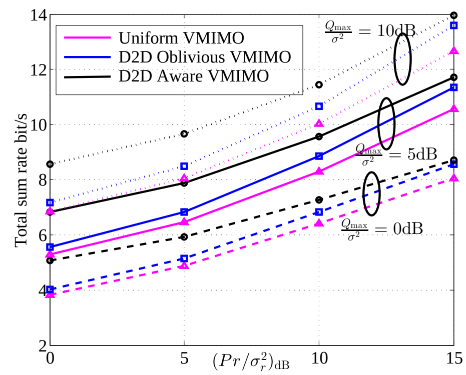
Step 0 *Set a virtual MIMO k, $\epsilon > 0$ and $\mathbf{Q}_k^{(0)} = \frac{P_{max}}{b}\mathbf{I}$.*

Step ℓ • *for $m = 1, \dots b$ if*

$$\mathbb{E}\mathcal{T}_m(\mathbf{Q}_k^{(\ell-1)} \leq \mathrm{tr}\boldsymbol{\Xi}^{-1}(\mathbf{Q}_k^{(\ell-1)})\mathbf{D}_k\boldsymbol{\Lambda}^{(m)}$$



(a)



(b)

Fig. 1. (a) Average total rate vs $Q_{\max}/\sigma_n^2$ in downlink for $P_r/\sigma_r^2 = 0,\ 5$ dB for the proposed system (solid lines), the benchmark D2D-oblivious V-MIMO system (dashed lines) and uniform power allocation (dot-dashed lines) and (b) Average total rate vs Pr/σ_r^2 for $Q_{\max}/\sigma_n^2 = 0, 5, 10$dB with a ULA array of $M = 64$ antennas and 4 users distributed over a sector.

$$\begin{cases} q_{km} = 0, & \text{if } \mathbb{E}\mathcal{T}_m(\mathbf{Q}_k) \leq \mathrm{tr}\boldsymbol{\Xi}^{-1}(\mathbf{Q}_k)\mathbf{D}_k\boldsymbol{\Lambda}^{(m)} \\ P_{\max}\left(\mathbb{E}\mathcal{T}_m(\mathbf{Q}_k) - \mathrm{tr}\boldsymbol{\Xi}^{-1}(\mathbf{Q}_k)\mathbf{D}_k\boldsymbol{\Lambda}^{(m)}\right) = n - \sum_{j=1}^{n} q_{kj}\mathrm{tr}\mathbb{E}(\mathcal{T}_j(\mathbf{Q}_k)\mathbf{F}_k) - \mathrm{tr}\boldsymbol{\Xi}^{-1}(\mathbf{Q}_k)\mathbf{D}_k\mathbf{T}(\mathbf{Q}_k)), & \text{elsewhere.} \end{cases} \tag{17}$$

set $\pi_{k,m} = 0$ *otherwise* $\pi_{k,m} = q_{k,m}^{(\ell-1)}$.

- *Build the diagonal matrix*
$$\boldsymbol{\Pi}_k = \mathrm{diag}(\pi_{k,1}, \pi_{k,2}, \ldots \pi_{k,b}).$$
- *for* $m = 1, \ldots b$, *set*
$$q_{k,m}^{(\ell)} = \frac{P_{\max}\pi_{k,m}\left(\mathbb{E}\mathcal{T}_m(\boldsymbol{\Pi}_k) - \mathrm{tr}\boldsymbol{\Xi}^{-1}(\boldsymbol{\Pi}_k)\mathbf{D}_k\boldsymbol{\Lambda}^{(m)}\right)}{n - \sum_{j=1}^{n} q_{kj}\mathrm{tr}\mathbb{E}(\mathcal{T}_j(\boldsymbol{\Pi}_k)\mathbf{F}_k) - \mathrm{tr}\boldsymbol{\Xi}^{-1}(\boldsymbol{\Pi}_k)\mathbf{D}_k\mathbf{T}(\boldsymbol{\Pi}_k)}$$
- *Build the diagonal matrix*
$$\mathbf{Q}_k^{(\ell)} = \mathrm{diag}(q_{k,1}^{(\ell)}, q_{k,2}^{(\ell)}, \ldots q_{k,b}^{(\ell)}).$$
- *If* $\|\mathbf{Q}_k^{(\ell)} - \mathbf{Q}_k^{(\ell-1)}\| > \epsilon$ *go back to step* ℓ *otherwise return* $\mathbf{Q}_k^{(\ell)}$.

If the D2D links are fast fading as the downlink channel, we can still apply the algorithm proposed for precoding design of the slow fading case assuming that the variance channel profile is given by

$$\widetilde{\mathbf{G}}_k^{(f)} = \boldsymbol{\Gamma}_k^{(f)}\left[\widetilde{\boldsymbol{\lambda}}_1, \widetilde{\boldsymbol{\lambda}}_2, \ldots, \widetilde{\boldsymbol{\lambda}}_n\right] \tag{19}$$

being $\boldsymbol{\Gamma}_k^{(f)}$ a diagonal matrix with elements

$$(\boldsymbol{\Gamma}_k^{(f)})_{jj} = \begin{cases} \left(\sigma_n^2 + \dfrac{P_j\sigma_r^2}{P_r\gamma_{k,j}}\right)^{-1}, & \text{for } j \neq k \\ \sigma_n^{-2}, & \text{for } j \neq k. \end{cases}$$

However, Proposition 1 does not hold and the characterization of the precoder structure is left for future studies.

IV. Simulation Results

We assess the performance of the D2D-aware V-MIMO scheme by simulations and compare it to the D2D-oblivious V-MIMO scheme proposed in [13] and a uniform power allocation. The system performance is expressed in terms of total sum rate. Note that the achievable rate for user k in cluster $\mathcal{C}$ based on the D2D-aware V-MIMO scheme is given by $R_k = n^{-1}\mathcal{I}(\mathbf{Q}_k^*)$ where $\mathcal{I}(\mathbf{Q}_k^*)$ is the solution of the optimization problem P1 and the factor n^{-1} is motivated by the fact that the transmission on the V-MIMO for user k occurs each n channel uses. Then, the total achievable rate in cluster $\mathcal{C}$ is given by

$$R_{\mathcal{C}} = \sum_{k\in\mathcal{C}} R_k = \frac{1}{n}\sum_{k\in\mathcal{C}}\mathcal{I}(\mathbf{Q}_k^*). \tag{20}$$

The setting considered in our simulations consists of a BS with a ULA of $M = 64$ antennas and 4 users in a cluster. The simulations account for the approximations due to the finite size of the ULA. In fact, for finite ULA the orthogonal steering vectors $\mathbf{f}_m = (1, \mathrm{e}^{-j2\pi m\cdot 1/M}, \ldots \mathrm{e}^{-j2\pi m\cdot(M-1)/M})^T$ only approximate the eigenvectors of the cluster covariance matrix such that the statistical properties of the matrix $\mathbf{A}_c$ assumed in Proposition 1 and 2 are only approximated. The relay channel is slow fading with variance determined by the classical pathloss model with attenuation exponent $\alpha = 2$. Fig. 1-a shows the average rate versus the ratio $Q_{\max}/\sigma_n^2$ for different values of P_r/σ_r^2. The comparison between the D2D-aware VMIMO and the D2D-oblivious VMIMO scheme shows a gain of about 2.5 and 3dB of the D2D-aware scheme at the expenses of the feedback of the slow fading channel coefficients. A uniform power allocation provides always a lower bound to the reference schemes. Fig. 1-b presents the average rate of the three analyzed schemes versus the ratio P_r/σ_r^2 for $Q_{\max}/\sigma^2 = 0, 5, 10$ dB. As the ratio P_r/σ_r^2 increases, the gap between the D2D-aware V-MIMO scheme and the D2D-oblivious V-MIMO scheme decreases. In fact, the V-MIMO tends to behave as an ideal point-to-point MIMO with all the user terminals co-located. On the contrary the gap between the D2D-oblivious V-MIMO and the scheme with uniform power allocation increases. Then, the gain due to the feedback of the statistical CSI is more significant when the quality of the D2D links is poor.

Acknowledgments

This work was supported by Huawei France Research Center.

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