Dual-regularized Precoding: A Robust Approach for D2D-Enabled Massive MIMO

Junting Chen, Haifan Yin, Laura Cottatellucci, and David Gesbert
EURECOM, 06410 Sophia Antipolis, France
Email:{chenju, yin, cottatel, gesbert}@eurecom.fr

***Abstract*—This paper exploits device-to-device (D2D) communications for exchanging the downlink channel state information (CSI) among users, so that the users can design better feedback strategies. Using a team decision approach for the feedback and precoding design, the users and the base station (BS) minimize a common mean squared error (MSE) metric based on their individual observations on the imperfect global CSI. The solutions are found to take similar forms as the regularized zero-forcing (RZF) precoder, with additional regularizations to capture the uncertainty of the exchanged CSI. Numerical results demonstrate superior performance of the proposed scheme over all D2D qualities.**

I. Introduction

CSI feedback is a challenging issue in frequency division multiplexing (FDD) massive multiple-input multiple-output (MIMO) systems. Existing works mainly focused on various quantization techniques to compress the CSI vector into a few number of bits [1]–[3]. An alternative approach for feedback reduction via a rate splitting encoding strategy at the massive MIMO transmitter was studied in [4], [5].

In recent years, D2D assisted MIMO transmission has attracted increasing attentions. With D2D communications, some users can act as relays to assist the data transmission to the target users, by reusing the radio resources of the cellular network through proper power control and adaptive precoder design [6]–[8]. While a lot of literature focuses on using D2D to deliver data streams, there are some works exploiting D2D to assist the *signaling* for MIMO cellular transmission [9]–[11]. Specifically, the authors in [10] proposed a *precoder feedback scheme* for FDD multiuser MIMO systems, where the users first obtain the global CSI via D2D, and then compute and feed back the precoder to the BS through the rate-limited uplink feedback channel. It is demonstrated in [10] that in the ideal case when users have perfect global CSI via infinite-rate D2D, the precoder feedback scheme can achieve signifiant throughput gain over the CSI feedback scheme. The analysis in [11] further shows that in such a case, the precoder feedback scheme reduces the interference leakage to $1/(K-1)$ of the CSI feedback scheme, where K is the number of users.

However, there are some limitations of the current D2D assisted feedback techniques. First, high quality D2D communication may not be easily realized in practical systems, since the D2D capacity is limited and there is transmission latency for the CSI exchange. Consequently, the assumption of perfect CSI exchange in [10] is unrealistic. Although the prior work [9] designed adaptive CSI exchange strategy for limited D2D capacity, efficient feedback strategies to the BS has not been studied so far for the case of noisy CSI exchange. Second, the precoder feedback schemes in [9]–[11] are not compatible with the conventional CSI feedback scheme, because it requires all the users to have the same D2D quality. However, in practice, it may happen that some users have D2D links and wish to perform precoder feedback, but the others have no D2D at all and have to perform CSI feedback.

To address these problems, this paper develops an advanced feedback and precoding strategy for the users and the BS under the practical scenarios that users exchange the CSI under *heterogeneous* D2D quality. A team decision approach is adopted, where the users and the BS follow a common MSE metric to minimize the total MSE of the received signals at the user side. Specifically, the users compute the feedback vector to minimize the expected MSE based on their individual observations of the global CSI, and the BS computes the expected minimum mean square error (MMSE) precoder based on the feedback from the users. We show that the solutions to such series of team decision problems have a *dual regularization* structure, where the feedback is given by the vector that maximizes the signal-to-interference-leakage-and-noise-ratio (SLNR) regularized by the D2D qualities, and the precoder is given by the RZF solution that is also regularized by the D2D qualities. The proposed dual-regularized feedback and precoding strategy bridge the gap between the conventional CSI feedback scheme [1]–[3] and the precoder feedback scheme [9]–[11], and it converges to the two existing schemes in the extremes of no D2D and perfect D2D, respectively. It is demonstrated that the proposed scheme can achieve significant throughput enhancement for all the users. Moreover, all the users still gain benefits in the heterogeneous case where some users have good D2D, but some other users do not have D2D.

II. System Model

Consider a K-user downlink MIMO system, where the BS equips with $N_t \geq K$ antennas and the users have single antenna. Consider uncorrelated channels and denote the downlink channel for user k as $\mathbf{h}_k^{\mathrm{H}}$, where $\mathbf{h}_k \in \mathbb{C}^{N_t}$ is a column vector and follows the distribution $\mathcal{CN}(\mathbf{0}, \mathbf{I})$. The channels between users are mutually independent.[1]

[1]For dependent channels, distributed source coding can also be used to design the D2D assisted feedback strategy [12]. However, this is beyond the scope of this paper.

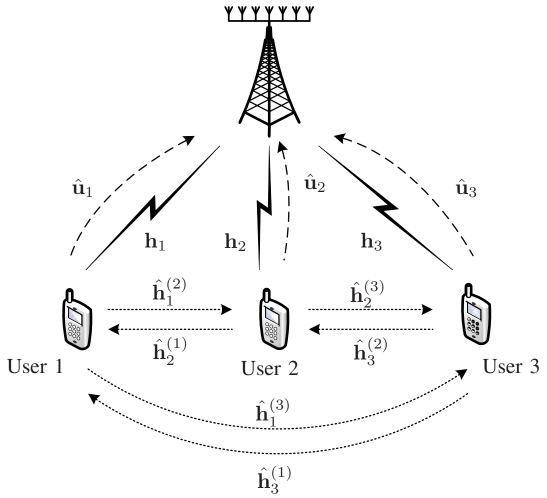


Figure 1. An example on the signaling structure for a three-user MIMO system, where the users exchange the quantized CSI via D2D.

A. CSI Exchange Strategy via D2D

User k knows $\mathbf{h}_k$ perfectly. In addition, to acquire the channels of other users, the users exploit reliable D2D links to directly exchange the CSI with each other. We are interested in the practical case where the D2D links have limited capacity and perhaps suffer from transmission latency. As a result, the CSI $\mathbf{h}_k$ of user k known by user j, denoted as $\hat{\mathbf{h}}_k^{(j)}$, is thus modeled as

$$\mathbf{h}_k = \alpha_{jk}\hat{\mathbf{h}}_k^{(j)} + \sqrt{1-\alpha_{jk}^2}\boldsymbol{\xi}_k^{(j)} \tag{1}$$

where $\boldsymbol{\xi}_k^{(j)}$ is a zero mean random vector that follows distribution $\mathcal{CN}(\mathbf{0},\mathbf{I})$ to model the noise due to the CSI exchange, and in addition, $\boldsymbol{\xi}_k^{(j)}$ and $\hat{\mathbf{h}}_k^{(j)}$ are uncorrelated. The parameter $\alpha_{jk} \in [0,1]$ captures the D2D quality for user j to receive the CSI from user k. In particular, $\alpha_{jk} = 0$ means there is no D2D from user k to user j, whereas, $\alpha_{jk} = 1$ means there is perfect D2D, and user j knows perfectly $\mathbf{h}_k$. The statistical information $\{\alpha_{jk}\}$ is assumed to be known by the users and the BS. Fig. 1 illustrates the signaling structure in the three-user case.

After the exchange of CSI, user k has the *imperfect* global CSI $\hat{\mathbf{H}}_k \in \mathbb{C}^{N_t\times K}$ given by

$$\hat{\mathbf{H}}_k = [\hat{\mathbf{h}}_1^{(k)}, \hat{\mathbf{h}}_2^{(k)}, \ldots \hat{\mathbf{h}}_{k-1}^{(k)}, \mathbf{h}_k, \hat{\mathbf{h}}_{k+1}^{(k)}, \ldots, \hat{\mathbf{h}}_K^{(k)}]. \tag{2}$$

B. Formulation of the Feedback and Precoding Problems

Each user has B bits for the feedback to the BS based on a codebook $\mathcal{C}_k$, which contains 2^B complex-valued N_t-dimensional vectors, unit-normed, and randomly and isotropically distributed in the N_t-dimensional sphere.

Based on the feedback from the users, the BS computes the precoder $\mathbf{W} \in \mathbb{C}^{N_t\times K}$ for the downlink transmission. The downlink received signal $\mathbf{y} = [y_1, y_2, \ldots, y_K]^{\mathrm{T}}$ at the user side is

$$\mathbf{y} = \mathbf{H}^{\mathrm{H}}\mathbf{W}\mathbf{x} + \mathbf{n} \tag{3}$$

where $\mathbf{x} \in \mathbb{C}^K$ is the vector of transmission symbols that satisfies $\mathbb{E}\{\mathbf{x}\mathbf{x}^{\mathrm{H}}\} = \mathbf{I}_K$, $\mathbf{W}$ is the precoder that the norm of each column is $\sqrt{P/K}$ (i.e., equal power allocation among the users), and $\mathbf{n} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_K)$ is the Gaussian noise.

From the signal model (3), the total MSE is given by

$$\begin{aligned}\mathsf{MSE}(\mathbf{W},\mathbf{H}) &\triangleq \mathrm{tr}\Big\{\mathbb{E}\left\{(\mathbf{y}-\mathbf{x})(\mathbf{y}-\mathbf{x})^{\mathrm{H}}\right\}\Big\} \\ &= \left\|\mathbf{H}^{\mathrm{H}}\mathbf{W} - \mathbf{I}\right\|_F^2 + K.\end{aligned} \tag{4}$$

The common goal of the users and the BS is to minimize the MSE in (4) subject to the constraint of equal power allocation P/K to each user.

We consider that the users and the BS make sequential team decisions to minimize the total MSE based on their individual information. Specifically, the feedback and precoding problems are formulated as follows.

Feedback: Each user k feeds back to the BS a discretized vector

$$\hat{\mathbf{u}}_k = \mathcal{Q}_k(\mathbf{U}_k^\star) \tag{5}$$

where the matrix $\mathbf{U}_k^\star$ is obtained as the solution to the following power-constrained MMSE problem

$$\begin{aligned}\underset{\mathbf{W}\in\mathbb{C}^{N_t\times K}}{\text{minimize}} \quad & \mathbb{E}\left\{\mathsf{MSE}(\mathbf{W},\mathbf{H})\,\middle|\,\hat{\mathbf{H}}_k\right\} \\ \text{subject to} \quad & \|\mathbf{w}_k\|^2 = P/K, \qquad k = 1,2,\ldots,K\end{aligned} \tag{6}$$

in which, the vector $\mathbf{w}_k$ denotes the kth column of $\mathbf{W}$ and the expectation is taken over the uncertainty of the global CSI $\mathbf{H}$ given the individual imperfect global CSI $\hat{\mathbf{H}}_k$. The quantizer $\mathcal{Q}_k(\cdot)$ is to be designed.

Precoding: Given the feedback $\hat{\mathbf{U}} = [\hat{\mathbf{u}}_1, \hat{\mathbf{u}}_2, \ldots, \hat{\mathbf{u}}_K]$ from all the users, the BS computes the precoder $\mathbf{W}^\star$ as the solution to the following problem

$$\begin{aligned}\underset{\mathbf{W}\in\mathbb{C}^{N_t\times K}}{\text{minimize}} \quad & \mathbb{E}\left\{\mathsf{MSE}(\mathbf{W},\mathbf{H})\,\middle|\,\hat{\mathbf{U}}\right\} \\ \text{subject to} \quad & \|\mathbf{w}_k\|^2 = P/K, \qquad k = 1,2,\ldots,K\end{aligned} \tag{7}$$

where the expectation is taken over the uncertainty of the global CSI $\mathbf{H}$ given the feedback $\hat{\mathbf{U}}$ from the users.

III. Feedback Design

A. The MMSE Solution based on Imperfect Global CSI

Using the notation $\hat{\mathbf{H}}_k$ in (2), we write the channel model in (1) into a compact form as

$$\mathbf{H} = \hat{\mathbf{H}}_k\mathbf{A}_k^{\frac{1}{2}} + \mathbf{E}_k\mathbf{S}_k^{\frac{1}{2}}$$

where

$$\mathbf{E}_k = [\boldsymbol{\xi}_1^{(k)}, \boldsymbol{\xi}_2^{(k)}, \ldots, \boldsymbol{\xi}_K^{(k)}]$$

and the columns $\boldsymbol{\xi}_j^{(k)}$ are independent. In addition, $\mathbf{A}_k$ and $\mathbf{S}_k$ are diagonal matrices with diagonal elements given by

$$[\mathbf{A}_k]_{(j,j)} = \begin{cases} \alpha_{kj}^2 & j \neq k \\ 1 & j = k, \end{cases}$$

and

$$[\mathbf{S}_k]_{(j,j)} = \begin{cases} 1-\alpha_{kj}^2 & j \neq k \\ 0 & j = k. \end{cases}$$

As a result, the total MSE (6) conditioned on user k's imperfect global CSI $\hat{\mathbf{H}}_k$ is thus given by

$$\mathbb{E}\left\{ \left\| (\hat{\mathbf{H}}_k \mathbf{A}_k^{\frac{1}{2}} + \mathbf{E}_k \mathbf{S}_k^{\frac{1}{2}})^{\mathrm{H}} \mathbf{W} - \mathbf{I} \right\|_F^2 \,\middle|\, \hat{\mathbf{H}}_k \right\} + K. \quad (8)$$

Note that since the optimal solution of the feedback problem (6) always satisfies the equality $\mathrm{tr}\{\mathbf{W}^{\mathrm{H}}\mathbf{W}\} = \sum_k \|\mathbf{w}_k\|^2 = P$, we consider an equivalent objective function as

$$f_k(\mathbf{W}, \hat{\mathbf{H}}_k) = \mathbb{E}\left\{ \left\| (\hat{\mathbf{H}}_k \mathbf{A}_k^{\frac{1}{2}} + \mathbf{E}_k \mathbf{S}_k^{\frac{1}{2}})^{\mathrm{H}} \mathbf{W} - \mathbf{I} \right\|_F^2 \,\middle|\, \hat{\mathbf{H}}_k \right\} + K \frac{\mathrm{tr}\left\{\mathbf{W}^{\mathrm{H}}\mathbf{W}\right\}}{P}. \quad (9)$$

As the power-constrained MMSE problem (6) does not have a closed form solution, we consider a relaxed MMSE problem that employs the equivalent objective function (9) and drops the power constraints $\|\mathbf{w}_k\|^2 = P/K$ as follows

$$\underset{\mathbf{W} \in \mathbb{C}^{N_t \times K}}{\text{minimize}} \quad f_k(\mathbf{W}, \hat{\mathbf{H}}_k). \quad (10)$$

The closed form solution to (10) is given in the following result.

Proposition 1 (Relaxed MMSE solution under imperfect global CSI): The optimal solution $\widetilde{\mathbf{U}}_k^\star$ to the relaxed MMSE problem (10) is given by

$$\widetilde{\mathbf{U}}_k^\star = \Big[\hat{\mathbf{H}}_k \mathbf{A}_k \hat{\mathbf{H}}_k^{\mathrm{H}} + \big(\sum_{j \neq k} (1-\alpha_{kj}^2) + \frac{K}{P} \big) \mathbf{I}_{N_t} \Big]^{-1} \hat{\mathbf{H}}_k \mathbf{A}_k^{\frac{1}{2}}. \quad (11)$$

Proof: Please refer to [13]. □

From Proposition 1, we obtain a relaxed MMSE solution $\mathbf{U}_k^\star$ to the feedback problem (6) for user k, and the kth column of $\mathbf{U}_k^\star$ is given by

$$\mathbf{u}_k^\star = \beta_k \Big[\hat{\mathbf{H}}_k \mathbf{A}_k \hat{\mathbf{H}}_k^{\mathrm{H}} + \big(\sum_{j \neq k} (1-\alpha_{kj}^2) + \frac{K}{P} \big) \mathbf{I}_{N_t} \Big]^{-1} \mathbf{h}_k \quad (12)$$

where β_k is a power scaling factor.

The above result (12) takes the similar form as the robust MMSE precoding under imperfect CSI at the BS, where the term $\sum_{j \neq k}(1-\alpha_{kj}^2)\mathbf{I}_{N_t}$ performs regularization due to the CSI uncertainty from the CSI exchange and the term K/P regularizes according to the SNR similar to RZF.

B. Vector Discretization

The MMSE solution (12) is computed in the continuous domain, and needs to be discretized into B bits for the feedback. In fact, we are only interested in the kth column of $\mathbf{U}_k^\star$, because in the special case of perfect D2D quality, the kth column of $\mathbf{U}_k^\star$ is the desired precoder for user k and only the kth column is needed to be fed back [11]. In the case of no D2D, the kth column of $\mathbf{U}_k^\star$ degenerates to the channel $\mathbf{h}_k$, which is also the desired vector to be fed back.

An intuitive solution is to find a vector from the codebook that is "closest" to the kth *normalized* column vector of $\mathbf{U}_k^\star$.[2] However, it is not known what a good distance measure would be for the "closeness", as $\mathbf{U}_k^\star$ has the physical meaning as a regularized precoder.[3] Alternatively, we exploit the equivalence between the pseudo-inverse solution (12) and the solution to a Rayleigh quotient maximization problem. Specifically, the result is given in the following lemma.

Lemma 1 (Equivalence between MMSE and SLNR): Let $\mathbf{H}$ be an $N_t \times K$ matrix with the kth column given by vector $\mathbf{h}_k$. For a positive definite matrix $\mathbf{Q}$, it holds that

$$(\mathbf{H}\mathbf{H}^{\mathrm{H}} + \mathbf{Q})^{-1}\mathbf{h}_k = c_k \mathbf{u}_k$$

where c_k is a complex-valued scalar and $\mathbf{u}_k$ is the solution to the following problem

$$\underset{\|\mathbf{u}\|=1}{\text{maximize}} \quad \frac{|\mathbf{h}_k^{\mathrm{H}}\mathbf{u}|^2}{\sum_{j \neq k} |\mathbf{h}_j^{\mathrm{H}}\mathbf{u}|^2 + \mathbf{u}^{\mathrm{H}}\mathbf{Q}\mathbf{u}}. \quad (13)$$

Proof: Please refer to [13]. □

As a result of Lemma 1, we can relate the pseudo-inverse solution (12) in continuous domain to a quotient maximization problem in the finite domain.

Proposition 2 (Feedback strategy for uncorrelated channels): The feedback strategy for user k is to choose a vector $\hat{\mathbf{u}}_k$ from the codebook $\mathcal{C}_k$ as the solution to the following problem

$$\underset{\mathbf{u} \in \mathcal{C}_k}{\text{maximize}} \quad \frac{|\mathbf{h}_k^{\mathrm{H}}\mathbf{u}|^2}{\sum_{j \neq k} \alpha_{kj}^2 \big|(\hat{\mathbf{h}}_j^{(k)})^{\mathrm{H}}\mathbf{u}\big|^2 + \sum_{j \neq k}(1-\alpha_{kj}^2) + \frac{K}{P}}. \quad (14)$$

When users have perfect global CSI, i.e., $\alpha_{kj} = 1$, they feed back the precoding vector that maximize the SLNR, whereas when users have no CSI from each other, i.e., $\alpha_{kj} = 0$, the feedback problem (14) degenerates to

$$\underset{\mathbf{u} \in \mathcal{C}_k}{\text{maximize}} \quad |\mathbf{h}_k^{\mathrm{H}}\mathbf{u}|^2 \quad (15)$$

and the users feed back the quantized CSI. The terms α_{kj}^2 and $1-\alpha_{kj}^2$ steer the feedback vector from a precoding vector to a CSI vector, according to the D2D quality.

IV. Precoder Design

Based on the feedback $\hat{\mathbf{U}}$ from the users, the precoder is designed by solving problem (7). Using the same trick to relax the precoding problem (7) as we did in (10), the relaxed closed-form precoding solution is given by

$$\mathbf{W}^\star = \Big(\mathbb{E}\big\{ \mathbf{H}\mathbf{H}^{\mathrm{H}} \,\big|\, \hat{\mathbf{U}} \big\} + \frac{K}{P}\mathbf{I}_{N_t} \Big)^{-1} \mathbb{E}\big\{ \mathbf{H} \,\big|\, \hat{\mathbf{U}} \big\} \mathbf{\Psi}^{\frac{1}{2}} \quad (16)$$

where $\mathbf{\Psi}$ is a diagonal matrix for power scaling.

Remark 1 (Channel feedback $\hat{\mathbf{H}}$ versus regularized feedback $\hat{\mathbf{U}}$): From the precoding formula (16), it seems that the proposed scheme still needs to extract the CSI $\mathbf{H}$ from the feedback $\hat{\mathbf{U}}$. One may wonder whether it is better to

[2] Note that under the power constraints $\|\mathbf{w}_k\| = P/K$, the BS implicitly knows the norms of the columns of $\mathbf{U}_k^\star$.

[3] For example, a good distance measure to discretize the MIMO channel is the geodesic on the Grassmann manifold, but such measure may not be meaningful to discretizing the precoder.

always feedback the CSI $\hat{\mathbf{U}} = \hat{\mathbf{H}}$. This is intuitively true only under infinite-rate feedback, i.e., $\hat{\mathbf{H}} = \mathbf{H}$. For finite-rate CSI feedback, there is quantization error for $\hat{\mathbf{H}}$, and quantization error propagates (or even badly scales) in the inversion step in (16). By contrast, the feedback matrix $\hat{\mathbf{U}}$ already contains the inversion as from (12) and (14).

The remaining challenge in (16) is to evaluate the terms $\mathbb{E}\{\mathbf{H}\mathbf{H}^{\mathrm{H}} \,|\, \hat{\mathbf{U}}\}$ and $\mathbb{E}\{\mathbf{H} \,|\, \hat{\mathbf{U}}\}$. Under uncorrelated channels, the channel $\mathbf{h}_k$ can be expressed in terms of the feedback vector $\hat{\mathbf{u}}_k$ in (14). The result is characterized in the following proposition.

Proposition 3 (Characterization of $\hat{\mathbf{u}}_k$): Consider the feedback scheme (14). The following holds for each user k,

$$\mathbf{h}_k = \theta_k \mathbf{G}_k \left(\sqrt{1-\epsilon_k^2}\,\hat{\mathbf{u}}_k + \epsilon_k \mathbf{z}_k \right) \tag{17}$$

where $\mathbf{z}_k \in \mathbb{C}^{N_t}$ is a unit norm vector that satisfies $\hat{\mathbf{u}}_k^{\mathrm{H}} \mathbf{z}_k = 0$ and $\mathbb{E}\{\mathbf{z}_k\} = \mathbf{0}$ with isotropic distribution, $\epsilon_k \in [0, 1]$ is a random variable that is independent to $\hat{\mathbf{u}}_k$ and $\mathbf{z}_k$, and θ_k is a scaling factor. In addition,

$$\mathbf{G}_k = \sum_{j \neq k} \alpha_{kj}^2 \hat{\mathbf{h}}_j^{(k)} (\hat{\mathbf{h}}_j^{(k)})^{\mathrm{H}} + q_k \mathbf{I}_{N_t} \tag{18}$$

where $q_k \triangleq \sum_{j \neq k} (1 - \alpha_{kj}^2) + K/P$. Moreover,

$$\frac{N_t - 1}{N_t} 2^{-\frac{B}{N_t - 1}} \leq \mathbb{E}\{\epsilon_k^2\} \leq 2^{-\frac{B}{N_t - 1}}$$

where the expectation is taken over the distributions of $\mathbf{h}_k$, $\hat{\mathbf{h}}_j^{(k)}$, and $\mathcal{C}_k$.

Proof: Please refer to [13]. □

With Proposition 3, we have the following result to approximate $\mathbb{E}\{\mathbf{H}\mathbf{H}^{\mathrm{H}} \,|\, \hat{\mathbf{U}}\}$ and $\mathbb{E}\{\mathbf{H} \,|\, \hat{\mathbf{U}}\}$.

Proposition 4: Under high signal-to-noise ratio (SNR) P and high feedback resolution B, we have the following approximations

$$\mathbb{E}\Big\{\mathbf{H}\mathbf{H}^{\mathrm{H}} \,|\, \hat{\mathbf{U}}\Big\} \approx \varpi \Big(\big(1 - 2^{-\frac{B}{N_t - 1}}\big) \hat{\mathbf{U}} \mathbf{\Omega} \hat{\mathbf{U}}^{\mathrm{H}} + 2^{-\frac{B}{N_t - 1}} \phi \mathbf{I} \Big)$$

where ϖ is some scalar, $\mathbf{\Omega} = \mathrm{diag}(q_1^2, q_2^2, \ldots, q_K^2)$, and

$$\phi \triangleq \frac{1}{N_t} \sum_{k=1}^{K} \Big(q_k^2 + \sum_{j \neq k} \big(\alpha_{kj}^4 (N_t + 1) + 2 \alpha_{kj}^2 q_k \big) \Big). \tag{19}$$

In addition, $\mathbb{E}\{\mathbf{H} \,|\, \hat{\mathbf{U}}\} \approx \hat{\mathbf{U}} \Upsilon$, where Υ is a diagonal matrix.

Proof: Please refer to [13]. □

The approximation in Proposition 4 is asymptotically accurate for high SNR P and large B for the feedback under both perfect CSI exchange $\alpha_{kj} = 1$ and no CSI exchange $\alpha_{kj} = 0$.

Based on Proposition 4, the MMSE precoder at the BS under cooperative feedback $\hat{\mathbf{U}}$ from the users is given in the following theorem.

Theorem 1 (Approximate MMSE precoder): The MMSE precoder that is the solution to the problem (7) can be approximately given by

$$\mathbf{W}^{\star} = \Big[\big(1 - 2^{-\frac{B}{N_t - 1}}\big) \hat{\mathbf{U}} \mathbf{\Omega} \hat{\mathbf{U}}^{\mathrm{H}} + \Big(2^{-\frac{B}{N_t - 1}} \phi + \frac{K}{P} \Big) \mathbf{I} \Big]^{-1} \hat{\mathbf{U}} \mathbf{\Psi}^{\frac{1}{2}} \tag{20}$$

where $\mathbf{\Psi}$ is a diagonal matrix for power scaling.

For perfect CSI exchange, $\alpha_{kj} = 1$, one can show that $\mathbf{W}^{\star} \approx \hat{\mathbf{U}}$, which is the same as the cooperative precoder feedback scheme studied in [9] and [11]. For no CSI exchange, $\alpha_{kj} = 0$, the feedback matrix is given by $\hat{\mathbf{U}} = \hat{\mathbf{H}} = [\hat{\mathbf{h}}_1, \hat{\mathbf{h}}_2, \ldots, \hat{\mathbf{h}}_K]$, and the solution (20) becomes

$$\mathbf{W}^{\star} = \Big[\big(1 - 2^{-\frac{B}{N_t - 1}}\big) \hat{\mathbf{H}} \hat{\mathbf{H}}^{\mathrm{H}} + \Big(\frac{K}{N_t} 2^{-\frac{B}{N_t - 1}} + \gamma \frac{K}{P} \Big) \mathbf{I} \Big]^{-1} \hat{\mathbf{H}} \mathbf{\Psi}^{\frac{1}{2}} \tag{21}$$

where $\gamma = (K - 1 + K/P)^{-2}$. As a comparison, the robust MMSE precoding scheme in [3] gives

$$\mathbf{W}^{\mathrm{RB}} = \Big[\hat{\mathbf{H}} \hat{\mathbf{H}}^{\mathrm{H}} + \Big(K 2^{-\frac{B}{N_t}} + \frac{K}{P} \Big) \mathbf{I} \Big]^{-1} \hat{\mathbf{H}}. \tag{22}$$

Note that (21) and (22) take a similar form, and the difference is mainly due to the different quantization techniques and power allocation strategies used.

V. Numerical Results

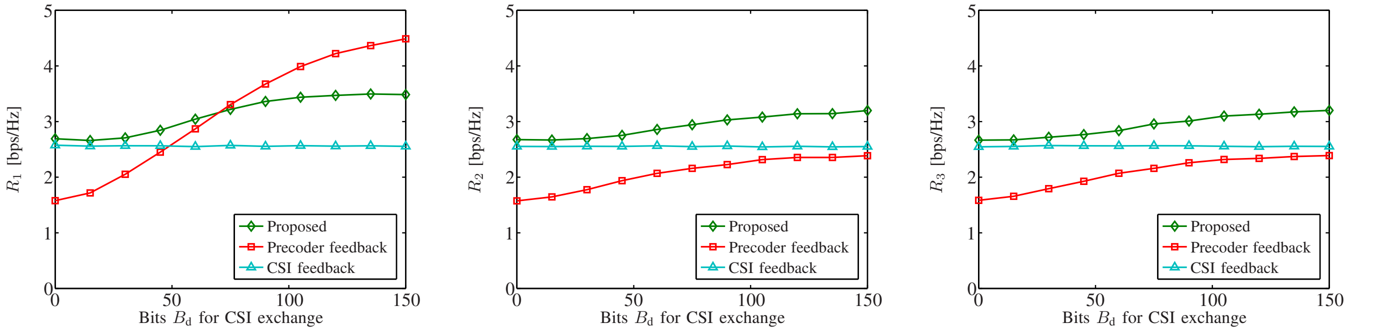
Consider the system model in Section II, where the BS has $N_t = 20$ antennas and there are $K = 3$ users. Each user has $B = 10$ bits for the feedback to the BS. Isotropic random vector quantization (RVQ) codebooks specified in Section II-B are used for the feedback. For the proposed scheme, consider that each user has B_{d} bits to exchange the quantized CSI vector with another user via D2D, and the parameter of CSI quality is modeled as $\alpha_{jk}^2 = \alpha^2 = 1 - 2^{-B_{\mathrm{d}}/N_t}$ [3]. The total downlink transmission power is $P = 20$ dB.

The proposed scheme is compared with the following baselines. (i) *Robust MMSE based on CSI feedback* [3]: Each user quantizes the channel according to (15) and conveys the CSI feedback to the BS. The BS computes the robust MMSE precoder according to (22). (ii) *Cooperative precoder feedback* [9]: Each user computes and feeds back the precoder according to (14) but assuming $\alpha_{kj} = 1$. The BS directly applies the feedback vectors as the precoder.

Two cases are evaluated. (a) *Case A:* All the users have the same D2D quality for CSI exchange, i.e., $\alpha_{kj} = \alpha$, $k \neq j$. (b) *Case B:* There is no D2D link between user 2 and 3, while all the other links have identical D2D quality for CSI exchange, i.e., $\alpha_{23} = \alpha_{32} = 0$, and $\alpha_{kj} = \alpha$ for $(k, j) \notin \{(2, 3), (3, 2)\}$.

Sum rate results: Fig. 2 shows the sum rate versus the number of bits B_{d} for CSI exchange. First, the proposed scheme outperforms both the precoder feedback scheme and the CSI feedback scheme over all D2D capacity for CSI exchange. In the regime of no CSI exchange, $B_{\mathrm{d}} = 0$, it approaches the CSI feedback scheme with robust MMSE precoder. In the regime of high quality CSI exchange, $B_{\mathrm{d}} = 150$ bits, it converges to the precoder feedback scheme. Second, by removing one D2D link in case B, the performance of the proposed scheme and the precoder feedback scheme both degrade, but the precoder feedback scheme degrades more at the high SNR regime.

Robustness: The performance under heterogeneous D2D quality for CSI exchange is demonstrated in Fig. 3, which shows the achievable downlink data rate for each user versus B_{d} under case B. The precoder feedback scheme boosts the



(a) User 1 (b) User 2 (c) User 3

Figure 3. Robustness: achievable downlink data rate for each user versus the number of bits B_d for CSI exchange under case B.

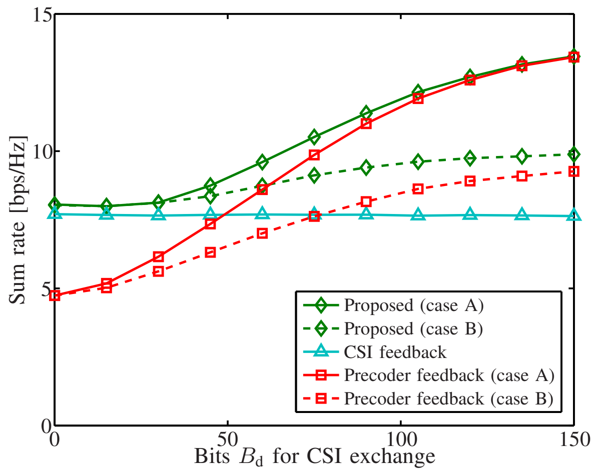


Figure 2. Sum rate versus the number of bits B_d for CSI exchange.

performance for user 1, but significantly sacrifices user 2 and 3, who achieve much lower data rate than the CSI feedback scheme. By contrast, the proposed scheme outperforms the CSI feedback scheme over all D2D capacity for all users. This shows that the proposed scheme is able to maintain fairness and robustness when users have heterogeneous D2D qualities.

VI. Conclusion

This paper proposes a dual-regularized feedback and precoding strategy for multiuser MIMO systems with limited feedback from the users to the BS, where the users can exploit short range D2D communications to exchange a portion of CSI with each other. The proposed strategy exploits such imperfect global CSI at the user side to feedback a regularized vector to the BS. Based on the feedback, the BS computes an MMSE type precoder regularized by the CSI uncertainty at the user side due to the noisy CSI exchange via D2D. Numerical results show that in terms of sum rate performance, the proposed scheme performs uniformly better than both the CSI feedback scheme and precoder feedback scheme from low to high D2D communication qualities.

Acknowledgment

The support of Huawei France Research Center is gratefully acknowledged. David Gesbert was also supported in part by the ERC under the European Union Horizon 2020 research and innovation program (Agreement no. 670896).

References

[1] N. Jindal, "MIMO broadcast channels with finite-rate feedback," *IEEE Trans. Inf. Theory*, vol. 52, no. 11, pp. 5045–5060, 2006.

[2] C. K. Au-Yeung and D. J. Love, "On the performance of random vector quantization limited feedback beamforming in a MISO system," *IEEE Trans. Wireless Commun.*, vol. 6, no. 2, pp. 458–462, 2007.

[3] A. D. Dabbagh and D. J. Love, "Multiple antenna MMSE based downlink precoding with quantized feedback or channel mismatch," *IEEE Trans. Commun.*, vol. 56, no. 11, pp. 1859–1868, 2008.

[4] C. Hao, Y. Wu, and B. Clerckx, "Rate analysis of two-receiver MISO broadcast channel with finite rate feedback: A rate-splitting approach," *IEEE Trans. Commun.*, vol. 63, no. 9, pp. 3232–3246, 2015.

[5] M. Dai, B. Clerckx, D. Gesbert, and G. Caire, "A rate splitting strategy for massive MIMO with imperfect CSIT," *IEEE Trans. Wireless Commun.*, no. 7, pp. 4611–4624, 2016.

[6] K. Jayasinghe, P. Jayasinghe, N. Rajatheva, and M. Latva-Aho, "Linear precoder-decoder design of MIMO device-to-device communication underlaying cellular communication," *IEEE Trans. Commun.*, vol. 62, no. 12, pp. 4304–4319, Dec. 2014.

[7] W. Zhong, Y. Fang, S. Jin, K. K. Wong, S. Zhong, and Z. Qian, "Joint resource allocation for device-to-device communications underlaying uplink MIMO cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 1, pp. 41–54, Jan. 2015.

[8] X. Lin, R. W. Heath, and J. G. Andrews, "The interplay between massive MIMO and underlaid D2D networking," *IEEE Trans. Wireless Commun.*, vol. 14, no. 6, pp. 3337–3351, Jun. 2015.

[9] J. Chen, H. Yin, L. Cottatellucci, and D. Gesbert, "Efficient feedback mechanisms for FDD massive MIMO under user-level cooperation," *submitted to IEEE Trans. Wireless Commun.*, 2016.

[10] H. Yin, L. Cottatellucci, and D. Gesbert, "Enabling massive MIMO systems in the FDD mode thanks to D2D communications," in *Proc. Asilomar Conf. on Signals, Systems, and Computers*, Nov. 2014, pp. 656–660.

[11] J. Chen, H. Yin, L. Cottatellucci, and D. Gesbert, "Precoder feedback versus channel feedback in massive MIMO under user cooperation," in *Proc. Asilomar Conf. on Signals, Systems, and Computers*, Nov. 2015, pp. 1449–1453.

[12] Q. Li, D. Gesbert, and N. Gresset, "A cooperative channel estimation approach for coordinated multipoint transmission networks," in *Proc. IEEE Int. Conf. Commun. Workshop*, 2015, pp. 94–99.

[13] J. Chen, H. Yin, L. Cottatellucci, and D. Gesbert, "Dual-regularized feedback and precoding of D2D assisted MIMO systems," *submitted to IEEE Trans. Wireless Commun.*, 2016.