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1 Introduction

In this contribution we examine a simple enhanced channel state information (CSI) reporting scheme that targets an improvement in DL MU-MIMO performance. In particular, we examine enhanced CSI reporting that includes an additional residual error norm feedback. This residual error norm captures the energy of the channel seen by a user that remains in the orthogonal complement of its reported precoder. Hence it is indicative of the interference that can potentially be caused to the user if it is co-scheduled with one or more other users. We then illustrate simple SINR formulas based on this enhanced CSI feedback that the eNB can exploit for MU-pairing. System level simulations presented in a companion contribution [9] reveal that even a wideband residual error norm feedback without any OLLA can yield good system throughput improvements. The proposed scheme is an update of the one proposed in [8].

2 Conventional MU-MIMO operation

The key hurdle that needs to be overcome in order to realize optimal MU-MIMO gains is the difficulty in modeling the received channel output seen by a user post-scheduling. While computing its CSI report, the user has an un-quantized estimate of its downlink channel but does not know the transmit precoder that will be employed by the base-station. On the other hand, the base station is free to select any transmit precoder but has to rely on the quantized CSI reported by the active users. To illustrate this, we consider a user of interest, say user-1, and model its received observations as

$$\mathbf{z}_1 = \mathbf{H}_1^\dagger \mathbf{x}_1 + \boldsymbol{\mu}_1, \quad (1)$$

where $\mathbf{H}_1^\dagger \in \mathbb{C}^{N \times M}$ denotes the channel matrix, with N, M being the number of receive antennas at the user and the number of transmit antennas at the eNB, respectively. $\boldsymbol{\mu}_1$ is the additive noise which assumed to be spatially white and \mathbf{x}_1 is the signal transmitted by the eNB. In the usual **SU-MIMO CSI reporting** the user estimates $\rho_1 \mathbf{H}_1$, where ρ_1 is the EPRE configured for the UE-1 and determines a desired precoder matrix $\hat{\mathbf{V}}_1$ of rank r_1 after assuming that no other user will be co-scheduled with it. As a byproduct, it also determines a linear filter \mathbf{F}_1 and r_1 SINRs, $\{\text{SINR}_1^i\}_{i=1}^{r_1}$. The understanding is that if the base station transmits using a transmit precoder $\sqrt{\frac{\rho_1}{r_1}} \hat{\mathbf{V}}_1$, then the effective SINR seen by the UE (after filtering using the filter \mathbf{F}_1 to remove interference among columns of $\mathbf{H}_1^\dagger \hat{\mathbf{V}}_1$) for the i^{th} layer (sent along the i^{th} column of $\hat{\mathbf{V}}_1$) will be SINR_1^i . Mathematically, the filtered received observation vector, under SU-MIMO transmission, can be modeled as

$$\mathbf{y}_1 = \mathbf{F}_1 \mathbf{z}_1 = \sqrt{\frac{\rho_1}{r_1}} \mathbf{F}_1 \mathbf{H}_1^\dagger \hat{\mathbf{V}}_1 \mathbf{s}_1 + \boldsymbol{\eta}_1, \quad (2)$$

where \mathbf{s}_1 is the symbol vector containing r_1 normalized QAM symbols and where $\text{diag}(\sqrt{\frac{\rho_1}{r_1}} \mathbf{F}_1 \mathbf{H}_1^\dagger \hat{\mathbf{V}}_1) = \text{diag}\{\sqrt{\text{SINR}_1^1}, \dots, \sqrt{\text{SINR}_1^{r_1}}\}$. The user feedbacks the PMI $\hat{\mathbf{V}}_1$ and quantized SINRs $\{\hat{\text{SINR}}_1^i\}_{i=1}^{r_1}$ to the eNB.

The eNB obtains $\hat{\mathbf{V}}_1$ and $\hat{\mathbf{D}}_1 = \frac{r_1}{\rho_1} \text{diag}\{\hat{\text{SINR}}_1^1, \dots, \hat{\text{SINR}}_1^{r_1}\}$ based on the user's SU-MIMO CSI report. For SU-MIMO transmission, the eNB assumes a post-scheduling model for user-1 by approximating (1) as

$$\mathbf{y}_1 \approx \hat{\mathbf{D}}_1^{1/2} \hat{\mathbf{V}}_1^\dagger \mathbf{U}_1 \mathbf{s}_1 + \boldsymbol{\eta}_1, \quad (3)$$

where $\boldsymbol{\eta}_1$ is assumed to a spatially white noise vector and \mathbf{U}_1 denotes the transmit precoder along which symbols to user-1 are sent. Furthermore, an approach quite popular in MU-MIMO studies is to employ the following model for the received output seen by user-1, when it is co-scheduled with other users in an MU-MIMO transmission:

$$\mathbf{y}_1 = \hat{\mathbf{D}}_1^{1/2} \hat{\mathbf{V}}_1^\dagger \mathbf{U}_1 \mathbf{s}_1 + \hat{\mathbf{D}}_1^{1/2} \hat{\mathbf{V}}_1^\dagger \mathbf{U}_{\bar{1}} \mathbf{s}_{\bar{1}} + \boldsymbol{\eta}_1, \quad (4)$$

where $\mathbf{U}_{\bar{1}}$ contains all the remaining columns of the transmit precoder used for the co-scheduled

streams. Letting $\mathbf{A} = [\mathbf{U}_1, \mathbf{U}_{\bar{1}}]$ denote the MU-MIMO transmit precoding matrix, with $\text{rank}(\mathbf{U}_1) = r'_1 \leq r_1$, the base-station can obtain the following approximation for the SINRs seen by user-1 post-scheduling.

$$\begin{aligned}\hat{\text{sinr}}_1^i &= \frac{\hat{\alpha}_1^i}{1 - \hat{\alpha}_1^i}, \\ \hat{\alpha}_1^i &= [(\mathbf{I} + \mathbf{A}^\dagger \hat{\mathbf{S}}_1 \mathbf{A})^{-1} \mathbf{A}^\dagger \hat{\mathbf{S}}_1 \mathbf{A}]_{i,i}, \quad 1 \leq i \leq r'_1,\end{aligned}\tag{5}$$

where $\hat{\mathbf{S}}_1 \triangleq \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1 \hat{\mathbf{V}}_1^\dagger$. Since this SINR approximation is obtained by ignoring the component of the user channel that lies in the orthogonal complement of $\hat{\mathbf{V}}_1$, *it is an over-estimation and can in-fact degrade system performance without appropriate compensation*. Consequently, in order to improve DL MU-MIMO performance CQI/PMI reporting enhancements targeting DL MU-MIMO operations have been considered by several companies [1–7].

3 Enhanced MU-MIMO operation

Here the user, when configured by the eNB, **reports SU-MIMO CSI plus a residual error term**. The eNB can configure a user (to report the additional feedback) in a semi-static manner. We consider a simple form of residual error referred to as the residual error norm. Then, using SU-MIMO rules the user first determines a PMI $\hat{\mathbf{V}}_1$ of some rank r_1 along with r_1 quantized SINRs $\{\hat{\text{SINR}}_1^i\}_{i=1}^{r_1}$. Note that r_1 can be determined by the user or it can be enforced by the eNB via codebook subset restriction. The residual error norm is determined by the user as

$$\tilde{\epsilon}_1 = \sqrt{\text{tr}(\mathbf{F}_1 \mathbf{H}_1^\dagger \mathbf{P}_1 \mathbf{H}_1 \mathbf{F}_1^\dagger)},\tag{6}$$

where $\text{tr}(\cdot)$ denotes the trace operation and $\mathbf{P}_1 = (\mathbf{I} - \hat{\mathbf{V}}_1 \hat{\mathbf{V}}_1^\dagger)$ is a projection matrix. Note that $\tilde{\epsilon}_1$ represents the residual total energy in the component of the filtered channel that lies in the orthogonal complement of the reported precoder $\hat{\mathbf{V}}_1$. The user reports the usual SU-MIMO CSI along with the residual error norm $\tilde{\epsilon}_1$ or a normalized residual error norm ϵ_1 computed using

$$\epsilon_1 = \sqrt{\text{tr}(\mathbf{F}_1 \mathbf{H}_1^\dagger \mathbf{P}_1 \mathbf{H}_1 \mathbf{F}_1^\dagger \tilde{\mathbf{D}}_1^{-1})},\tag{7}$$

where $\tilde{\mathbf{D}}_1 = \text{diag}\{\text{SINR}_1^1, \dots, \text{SINR}_1^{r_1}\}$.

The eNB can use the residual error norms reported by the users to determine accurate SINRs for any choice of user pairing in MU-MIMO. To achieve this, it employs a finer approximation of the filtered channel matrix ($\mathbf{F}_1\mathbf{H}_1^\dagger$) of user-1 given by

$$\hat{\mathbf{D}}_1^{1/2}(\hat{\mathbf{V}}_1^\dagger + \mathbf{R}_1^\dagger\mathbf{Q}_1^\dagger), \quad (8)$$

where $\mathbf{Q}_1 \in \mathbb{C}^{M \times M-r_1}$ is a semi-unitary matrix whose columns lie in the orthogonal complement of $\hat{\mathbf{V}}_1$, i.e. $\mathbf{Q}_1^\dagger\hat{\mathbf{V}}_1 = \mathbf{0}$ and $\mathbf{R}_1 \in \mathbb{C}^{M-r_1 \times r_1}$ is a matrix which satisfies the Frobenius-norm constraint $\|\mathbf{R}_1\|_F^2 \leq \frac{\rho_1}{r_1}\epsilon_1^2$, where $\epsilon_1 > 0$ is the normalized residual error norm reported by user-1. Suppose the transmit precoder \mathbf{U} is parsed as $\mathbf{U} = [\mathbf{U}_1, \mathbf{U}_{\bar{1}}]$. For a well designed transmit precoder, the eNB can make the reasonable assumption that \mathbf{U}_1 (almost) lies in the span of $\hat{\mathbf{V}}_1$ whose columns represent the preferred directions along which user-1 wishes to receive its intended signal (so that $\mathbf{Q}_1^\dagger\mathbf{U}_1 \approx \mathbf{0}$). Then, a model more tuned to MU-MIMO operation can be obtained in which the channel output seen by user-1 post MU-MIMO scheduling is modeled as

$$\mathbf{y}_1 = \hat{\mathbf{D}}_1^{1/2}\hat{\mathbf{V}}_1^\dagger\mathbf{U}_1\mathbf{s}_1 + \hat{\mathbf{D}}_1^{1/2}(\hat{\mathbf{V}}_1^\dagger + \mathbf{R}_1^\dagger\mathbf{Q}_1^\dagger)\mathbf{U}_{\bar{1}}\mathbf{s}_{\bar{1}} + \boldsymbol{\eta}_1, \quad (9)$$

The model in (9) accounts for the fact that the component of $\mathbf{U}_{\bar{1}}$ in the orthogonal complement of $\hat{\mathbf{V}}_1$ can also cause interference to the UE. Notice that when only SU-MIMO CSI along with the normalized residual error norm is reported by the users, in the model in (9) the eNB can only infer that the semi-unitary matrix \mathbf{Q}_1 lies in the subspace determined by $\mathbf{I} - \hat{\mathbf{V}}_1\hat{\mathbf{V}}_1^\dagger$ and \mathbf{R}_1 is also not known except for the fact that $\text{tr}(\mathbf{R}_1^\dagger\mathbf{R}_1) = \frac{\rho_1}{r_1}\epsilon_1^2$.

We illustrate an important instance of how the eNB can utilize the model in (9) for MU-MIMO SINR computation by considering the practically important MU-MIMO configuration, which is co-scheduling a user-pair. We first consider co-scheduling two users with one stream per-user so that both $\mathbf{U}_1 = \mathbf{u}_1$ and $\mathbf{U}_{\bar{1}} = \mathbf{u}_{\bar{1}}$ are rank-1 vectors. Using the model in (9), we will compute the worst-case SINR obtained by minimizing the SINR over all feasible choices of $\mathbf{R}_1, \mathbf{Q}_1$. Without loss of generality, we assume \mathbf{Q}_1 to be a deterministic $M \times (M - r_1)$ semi-unitary matrix whose columns are the basis of the orthogonal complement of $\hat{\mathbf{V}}_1$ and consider all possible $(M - r_1) \times r_1$

matrices \mathbf{R}_1 satisfying the constraint that $\text{tr}(\mathbf{R}_1^\dagger \mathbf{R}_1) \leq \frac{\rho_1}{r_1} \epsilon_1^2$. Further, to obtain a conservative SINR estimate, the eNB can assume that the UE employs a simple MRC receiver, i.e., user-1 is assumed to use the linear combiner $\mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1^{1/2}$ on the model in (9). Then, the worst-case SINR can be expressed as:

$$\min_{\mathbf{R}_1 \in \mathbb{C}^{M-r_1 \times r_1}: \|\mathbf{R}_1\|_F^2 \leq \frac{\rho_1}{r_1} \epsilon_1^2} \frac{\|\mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1^{1/2}\|^4}{\|\mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1^{1/2}\|^2 + |\mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1 (\hat{\mathbf{V}}_1^\dagger + \mathbf{R}_1^\dagger \mathbf{Q}_1^\dagger) \mathbf{u}_{\bar{1}}|^2}. \quad (10)$$

Simple manipulations reveal that (10) is equal to

$$\frac{\|\mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1^{1/2}\|^4}{\|\mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1^{1/2}\|^2 + (|\mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1 \hat{\mathbf{V}}_1^\dagger \mathbf{u}_{\bar{1}}| + \sqrt{\frac{\rho_1}{r_1}} \epsilon_1 \|\mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1\| \|\mathbf{Q}_1^\dagger \mathbf{u}_{\bar{1}}\|)^2} \quad (11)$$

which in turn can be simplified as

$$\frac{\|\mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1^{1/2}\|^4}{\|\mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1^{1/2}\|^2 + (|\mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1 \hat{\mathbf{V}}_1^\dagger \mathbf{u}_{\bar{1}}| + \sqrt{\frac{\rho_1}{r_1}} \epsilon_1 \|\mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1\| \sqrt{\mathbf{u}_{\bar{1}}^\dagger (\mathbf{I} - \hat{\mathbf{V}}_1 \hat{\mathbf{V}}_1^\dagger) \mathbf{u}_{\bar{1}}})^2} \quad (12)$$

We next consider co-scheduling two users with one stream for user-1 so that $\mathbf{U}_1 = \mathbf{u}_1$ is a rank-1 vector and two streams for the other user so that $\mathbf{U}_{\bar{1}}$ is a rank-2 matrix. As before, to obtain a conservative SINR estimate, the eNB can assume that the UE employs a simple MRC receiver, and the worst-case SINR can be expressed as:

$$\min_{\mathbf{R}_1 \in \mathbb{C}^{M-r_1 \times r_1}: \|\mathbf{R}_1\|_F^2 \leq \frac{\rho_1}{r_1} \epsilon_1^2} \frac{\|\mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1^{1/2}\|^4}{\|\mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1^{1/2}\|^2 + \|\mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1 (\hat{\mathbf{V}}_1^\dagger + \mathbf{R}_1^\dagger \mathbf{Q}_1^\dagger) \mathbf{U}_{\bar{1}}\|^2}. \quad (13)$$

Next let $\mathbf{a} = \mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1 \hat{\mathbf{V}}_1^\dagger \mathbf{U}_{\bar{1}}$ and $\mathbf{b} = \mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1$ and $\mathbf{S} = \mathbf{U}_{\bar{1}}^\dagger \mathbf{Q}_1 \mathbf{Q}_1^\dagger \mathbf{U}_{\bar{1}} = \mathbf{U}_{\bar{1}}^\dagger (\mathbf{I} - \hat{\mathbf{V}}_1 \hat{\mathbf{V}}_1^\dagger) \mathbf{U}_{\bar{1}}$. Let the eigen value decomposition of \mathbf{S} be $\mathbf{S} = \mathbf{E} \mathbf{\Lambda} \mathbf{E}^\dagger$, where $\mathbf{\Lambda} = \text{diag}\{\lambda_1^2, \lambda_2^2\}$ and expand the 1×2 vector \mathbf{b} as $\mathbf{b} = \|\mathbf{b}\| [1, 0] \mathbf{A}^\dagger$, where \mathbf{A} is a 2×2 unitary matrix. Then, letting $\tilde{\mathbf{a}} = [\tilde{a}_1, \tilde{a}_2] = \mathbf{a} \mathbf{E}$, we can show that

$$\begin{aligned} & \max_{\mathbf{R}_1 \in \mathbb{C}^{M-r_1 \times r_1}: \|\mathbf{R}_1\|_F^2 \leq \frac{\rho_1}{r_1} \epsilon_1^2} \left\{ \|\mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1 (\hat{\mathbf{V}}_1^\dagger + \mathbf{R}_1^\dagger \mathbf{Q}_1^\dagger) \mathbf{U}_{\bar{1}}\|^2 \right\} = \\ & \max_{x, y \in \mathbb{R}^+: x^2 + y^2 \leq \frac{\rho_1}{r_1} \epsilon_1^2} \left\{ (|\tilde{a}_1| + \|\mathbf{b}\| \lambda_1 x)^2 + (|\tilde{a}_2| + \|\mathbf{b}\| \lambda_2 y)^2 \right\} \end{aligned} \quad (14)$$

(14) is a non-convex optimization problem and letting $c_1 = \lambda_1 \|\mathbf{b}\|$, $c_2 = \lambda_2 \|\mathbf{b}\|$ and $\check{\epsilon} = \sqrt{\frac{\rho_1}{r_1}} \epsilon_1$, we approximate (14) by

$$\max \left\{ (|\tilde{a}_1| + c_1 \check{\epsilon})^2 + |\tilde{a}_2|^2, (|\tilde{a}_2| + c_2 \check{\epsilon})^2 + |\tilde{a}_1|^2 \right\}. \quad (15)$$

Using (14) in (13) we can obtain an approximate SINR given by

$$\frac{\|\mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1^{1/2}\|^4}{\|\mathbf{u}_1^\dagger \hat{\mathbf{V}}_1 \hat{\mathbf{D}}_1^{1/2}\|^2 + \max \{ (|\tilde{a}_1| + c_1 \check{\epsilon})^2 + |\tilde{a}_2|^2, (|\tilde{a}_2| + c_2 \check{\epsilon})^2 + |\tilde{a}_1|^2 \}}. \quad (16)$$

Indeed the steps used to obtain the approximate SINRs in (12) and (16) can be readily extended to obtain the approximate SINRs for all permissible user co-scheduling configurations, all of which must satisfy co-scheduling no more than four streams with no more than two streams per-user.

4 Conclusions

In this contribution, we considered enhancements to the MU-MIMO operation by enhancing the user CSI reporting which enables more accurate MU-MIMO SINR computation at the eNB. In particular, we examined residual error norm feedback in which the user also reports a residual error norm term that captures the energy of the channel that remains in the orthogonal complement of the reported precoder. A companion contribution [9] shows that even a wideband residual error norm feedback allows for good system throughput improvements that are not dependent on an effective OLLA implementation.

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