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1 Introduction

In this contribution, we examine a broad framework for enhanced CSI reporting by the users in order to obtain an improvement in MU-MIMO performance. We also illustrate mechanisms using which the eNB can exploit such enhanced CSI feedback. Initial system level simulations a simple form of enhanced feedback indicate substantial system throughput improvements in homogenous networks and more modest improvements over heterogenous networks. This document is a revised re-submission of [7] updated with new description and simulation results.

2 Background

In the recent RAN-1 meetings (62-bis and 63 in particular), CQI/PMI reporting enhancements targeting DL MU-MIMO operations on PUSCH 3-1 as well as PUSCH 3-2 were considered by several companies [2-6, 8]. The proposed enhancement to PUSCH 3-2 comprised enabling sub-band PMI reporting in addition to the sub-band CQI reporting. On the other hand, enhancements to PUSCH 3-1 that were considered suggested that in addition to Rel-8 Mode 3-1 feedback, a UE can be configured via higher layer signalling to report [1]:

- A wideband PMI calculated assuming restricted rank equal to one, along with a per-subband CQI targeting MU-MIMO operation.
- The MU-MIMO CQI is computed assuming the interfering PMIs are orthogonal to the SU-MIMO rank 1 PMI and for 4 TX, the total number of co-scheduled layers is assumed to be 4 at the time of MU CQI computation [1].

Further, uniform power allocation among the 4 layers was taken to be the baseline and non-uniform power allocation was also examined by some companies. Unfortunately, a consensus on these enhancements could not be achieved in time for Rel-10. As a result no enhancements targeting MU-MIMO on either PUSCH 3-1 or PUSCH 3-2 have been included in Rel-10.

3 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 is 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 feeds back 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.

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

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.*

4 Enhanced MU-MIMO operation

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

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

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

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

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

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 $\mathbf{U} = [\mathbf{U}_1, \mathbf{U}_\perp]$. 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 $\text{tr}(\mathbf{R}_1^\dagger \mathbf{R}_1) = \frac{\rho_1}{r_1} \epsilon_1^2$.

For brevity, we illustrate one instance of how the eNB can utilize the model in (9) for MU-MIMO SINR computation by considering a practically important MU-MIMO configuration, which is co-scheduling a user-pair 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 \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:

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

which can be simplified as

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

Note that in case zero-forcing (ZF) transmit precoding is used (11) further simplifies to

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

Parameter	Assumption
Deployment scenario	IMT Urban Micro (UMi) and Urban Macro (UMa)
Duplex method and bandwidth	FDD: 10MHz for downlink
Cell layout	Hex grid 19 sites, 3 cells/site
Transmission power at BS	46 dBm
Number of users per sector	10
Network synchronization	Synchronized
Antenna configuration (eNB)	4 TX cross-polarized ant., $0.5\text{-}\lambda$ spacing
Antenna configuration (user)	2 RX cross-polarized ant.
Downlink transmission scheme	Dynamic SU/MU-MIMO scheduling; MU-MIMO pairing: Max 2 users/RB;
Codebook	Rel. 8 codebook
Downlink scheduler	PF in time and frequency
Scheduling granularity:	5 RBs
Feedback assumptions	5ms periodicity and 4ms delay; Sub-band CQI and PMI feedback without errors.
Sub-band granularity:	5 RBs
Downlink HARQ scheme	Chase Combining
Downlink receiver type	LMMSE
Channel estimation error	NA
Feedback channel error	NA
Control channel and reference signal overhead	3 OFDM symbols for control; Used TBS tables in TS 36.213

Table 1: Simulation Parameters

5 Simulation Results

We now evaluate the MU-MIMO performance with the different types of channel reports and enhancement methods via system level simulations.

5.1 Performance of MU-MIMO in Homogenous Networks

We first consider a homogenous network for which the simulation parameters are summarized in Table 1. The cell average and the 5% cell edge spectral efficiencies of baseline scheme with SU-MIMO CSI user reports are provided in Table 2. IMT Urban Micro (UMi) channel model is considered here. The ZF transmit precoding is employed for all MU-MIMO transmissions. Also included are the spectral efficiencies for the case when a rank restriction, i.e., $r_{\max} = 1$ is imposed on all active users via codebook subset restriction. Each user then reports its enhanced feedback including SU-MIMO CSI and the corresponding normalized residual error norm. Next, we consider

MU-MIMO/SU-MIMO	cell average	5% cell-edge
Baseline $r_{\max} = 2$	2.3576	0.0647
Enhanced feedback $r_{\max} = 1$	2.4815 (5.26%)	0.0766 (18.4%)
Enhanced feedback (fixed rank)	2.4125 (2.33%)	0.0686 (6.03%)
SU-MIMO plus rank-1 enhanced feedback	2.5567 (8.45%)	0.0736 (13.8%)
Enhanced feedback (dynamic rank selection)	2.5854 (9.66%)	0.0728 (12.5%)

Table 2: Spectral efficiency of MU-MIMO with near orthogonal transmit precoding with zero-forcing (ZF); Baseline SU-MIMO feedback or enhanced CSI feedback by the users. Relative percentage gains are over the baseline scheme. The channel model is ITU Urban Micro (UMi).

the case when the rank one restriction is removed and each user first determines and reports its SU-MIMO CSI (for the rank it considers best) followed by the normalized residual error norm. Note that in this case at the eNB scheduler we fix each user's transmission rank to be equal to its reported rank, i.e., if a user has reported rank-2 (rank-1), it will be served using rank-2 (rank-1) if scheduled. This restriction on scheduling flexibility limits the gains. We then consider the case when each user determines and reports its SU-MIMO CSI (for the rank it considers best). Then, if the determined rank is one, it reports the normalized residual error norm. However, if the determined rank is two, it determines and reports a rank-1 precoder along with the corresponding normalized residual error norm. Notice that this form of enhanced feedback (referred to in Table 2 as SU-MIMO-plus-rank-1 enhanced feedback) allows for a more substantial system throughput gain. Finally, we consider the case that the user reports its SU-MIMO CSI followed by the normalized residual error norm. At the base station, the scheduler determines the user's transmission rank which could be lower than its reported rank. We can see that with rank overwritten but without additional rank-1 PMI feedback, the proposed scheme can still achieve a large gain over the baseline scheme. Note that the cell average performance for this case is even slightly better than the case of SU-MIMO-plus-rank-1 enhanced feedback. Further, no OLLA was applied to any scheme involving enhanced CSI feedback so that the gains obtained are quite robust.

Similar results can be obtained for IMT Urban Macro (UMa) channel model which are provided in Table 3.

MU-MIMO/SU-MIMO	cell average	5% cell-edge
Baseline $r_{\max} = 2$	2.2645	0.0654
Enhanced feedback $r_{\max} = 1$	2.3689 (4.61%)	0.0780 (19.3%)
Enhanced feedback (fixed rank)	2.3376 (3.23%)	0.0736 (12.5%)
SU-MIMO plus rank-1 enhanced feedback	2.4552 (8.42%)	0.0774 (18.4%)
Enhanced feedback (dynamic rank selection)	2.4739 (9.25%)	0.0769 (17.6%)

Table 3: Spectral efficiency of MU-MIMO with near orthogonal transmit precoding with zero-forcing (ZF); Baseline SU-MIMO feedback or enhanced CSI feedback by the users. Relative percentage gains are over the baseline scheme. The channel model is ITU Urban Macro (UMa).

5.2 Performance of MU-MIMO in Heterogenous Networks

We now consider a heterogenous network for which the simulation parameters are summarized in Table 4. Table 5 provides the cell average and 5% cell-edge spectral efficiencies of both SU-MIMO and MU-MIMO. In order to obtain the MU-MIMO results we imposed a rank-1 codebook restriction on all users. Further, each user was configured to report a normalized residual error norm in addition to its SU-MIMO CSI report. We modeled the post-scheduling user received output as (9) and considered the MRC SINR approximation (12). No additional user pooling or SINR offset or OLLA was applied. We note that while more modest gains are obtained using residual error feedback, these gains are robust and can improve with other forms for enhanced feedback.

6 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. Our results using a simple form of enhanced feedback show substantial system throughput improvements in homogenous networks and more modest improvements in heterogenous networks. One important feature of the gains obtained is that they are quite robust in the sense that they are not dependent on an effective OLLA implementation.

References

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Parameter	Assumption
Deployment scenario	Scenario 3: Heterogeneous network with low power RRHs within the macrocell coverage - 1 cell with 2 low-power nodes (LPNs) ITU UMa for Macro, UMi for low power node
Duplex method and bandwidth	FDD: 10MHz for downlink
Cell layout	Hex grid 19 sites, 3 cells/site
Antenna Height	Macro: 25m; LPN: 10m
Number of users per sector	Config4b: 30
Network synchronization	Synchronized
UE noise figure	9dB
Minimum Distance	Macro - RRH/Hotzone: $> 75m$ Macro - UE : $> 35m$ RRH/Hotzone - RRH/Hotzone: $> 40m$ RRH/Hotzone - UE : $> 10m$
Handover margin	1dB
Indoor-outdoor modeling	100% of users are dropped outdoor
Antenna configuration (eNB)	4 TX co-pol. ant., 0.5λ spacing for both Macro Cell and LPN
Antenna configuration (user)	2 RX co-pol. ant., 0.5λ spacing
Antenna pattern	For macro eNB: 3D, tilt 12 degree. For low-power node: 2D
Downlink transmission scheme	SU-MIMO: Each user can have rank 1 or 2 MU-MIMO: Max 2 users/RB; Each user can have rank 1
Codebook	Rel. 8 codebook
Downlink scheduler	PF in time and frequency
Scheduling granularity:	5 RBs
Feedback assumptions	5ms periodicity and 4ms delay; Sub-band CQI and PMI feedback without errors.
Sub-band granularity:	5 RBs
Downlink HARQ scheme	Chase Combining
Downlink receiver type	LMMSE
Channel estimation error	NA
Feedback channel error	NA
Control channel and reference signal overhead	3 OFDM symbols for control; Used TBS tables in TS 36.213

Table 4: Simulation Parameters: Heterogeneous network with low power RRHs within the macrocell coverage

MU-MIMO/SU-MIMO	Average Cell SE	5% Cell-edge
SU-MIMO Overall	2.8621	0.078
SU-MIMO Macro-cell	2.2025	0.0622
SU-MIMO LPN-RRH	3.1919	0.0904
MU-MIMO Overall	3.1526 (10.15%, 5.59%)	0.0813
MU-MIMO Macro-cell	2.5322 (14.97%, 8.54%)	0.0721
MU-MIMO LPN-RRH	3.4628 (8.49%, 4.91%)	0.1036

Table 5: Spectral efficiency of SU-MIMO/MU-MIMO in Heterogenous Networks; For MU-MIMO Rank-1 codebook restriction is imposed on all users and enhanced feedback is obtained from all users. Relative percentage gains are over SU-MIMO and MU-MIMO without enhanced feedback, respectively.