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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 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 Enhanced 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. 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. We first consider a simple (baseline) approach for modeling the received output seen by a user of interest (say user-1) post-scheduling. Such an approach is quite popular in MU-MIMO studies. Here, essentially the received output seen by user-1 post-scheduling is modeled as

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

where $\boldsymbol{\eta}_1 \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$ is the additive noise. \mathbf{U}_1 contains columns of the transmit precoder along which symbols to user-1 are sent whereas $\mathbf{U}_{\bar{1}}$ contains all the remaining columns used for the co-scheduled streams. $\hat{\mathbf{D}}_1^{1/2}$ is a diagonal matrix of *effective channel gains* and $\hat{\mathbf{V}}_1$ is a semi-unitary matrix whose columns represent the preferred *channel directions*.

Under SU-MIMO CSI reporting rules, the UE assumes a post-scheduling model as in (1) where the matrix $\mathbf{U}_{\bar{1}} = \mathbf{0}$ and $\hat{\mathbf{D}}_1^{1/2}, \hat{\mathbf{V}}_1$ are equal to the diagonal matrix of the unquantized dominant *singular values* and the unquantized dominant *right singular vectors*, respectively, of its downlink channel matrix \mathbf{H}_1^\dagger . In other words, the UE assumes that there will be no other users co-scheduled with it on its allocated resource blocks. The UE then determines a precoder $\hat{\mathbf{G}}_1$ of a preferred rank r_1 and reports the corresponding quantized SINRs $\{\hat{\text{SINR}}_1^i\}_{i=1}^{r_1}$ as CQIs.¹ The understanding is that if the base station selects a transmit precoder such that $\mathbf{U}_{\bar{1}} = \mathbf{0}$ and $\mathbf{U}_1 = \frac{\rho_1}{r_1} \hat{\mathbf{G}}_1$, where ρ_1 is the EPRE configured for the UE-1, then the effective SINR seen by the UE (after filtering using a

¹Note that when $r_1 \geq 2$ the SINRs are combined into two CQIs.

filter \mathbf{F}_1 to remove interference among columns of \mathbf{U}_1) for the i^{th} column of \mathbf{U}_1 will be SINR_1^i .

On the other hand, at the base station end we construct a model as in (1) using the CQI(s) and PMI reported by user 1. The CQI(s) are first mapped back to $\{\text{SINR}_1^i\}_{i=1}^{r_1}$. Then we set $\hat{\mathbf{V}}_1 = \hat{\mathbf{G}}_1$ and the matrix $\hat{\mathbf{D}}_1$ to be $\frac{r_1}{\rho_1} \text{diag}\{\text{SINR}_1^1, \dots, \text{SINR}_1^{r_1}\}$. Letting $\mathbf{A} = [\mathbf{U}_1, \mathbf{U}_{\bar{1}}]$ denote the 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.

$$\begin{aligned} \hat{\text{sinr}}_1^i &= \frac{\hat{\alpha}_1^i}{1 - \hat{\alpha}_1^i}, \\ \hat{\alpha}_1^i &= [(\mathbf{I} + \mathbf{A}^\dagger \hat{\mathbf{S}}_1 \mathbf{A})^{-1} \mathbf{A}^\dagger \hat{\mathbf{S}}_1 \mathbf{A}]_{i,i}, \quad 1 \leq i \leq r'_1, \end{aligned} \quad (2)$$

where $\hat{\mathbf{S}}_1 \triangleq \hat{\mathbf{G}}_1 \hat{\mathbf{D}}_1 \hat{\mathbf{G}}_1^\dagger$. Since this SINR approximation is obtained by ignoring the component of the user channel that lies in the orthogonal complement of $\hat{\mathbf{G}}_1$, it is an over-estimation and can in-fact degrade system performance without appropriate compensation.

Next, consider a finer modeling more tuned to MU-MIMO operation. Here, we assume that the channel output seen by user-1 post-scheduling can be modeled as

$$\mathbf{y}_1 = \hat{\mathbf{D}}_1^{1/2} \hat{\mathbf{V}}_1^\dagger \mathbf{U}_1 \mathbf{s}_1 + \hat{\mathbf{D}}_1^{1/2} (\hat{\mathbf{V}}_1^\dagger + \mathbf{R}_1^\dagger \mathbf{Q}_1^\dagger) \mathbf{U}_{\bar{1}} \mathbf{s}_{\bar{1}} + \boldsymbol{\eta}_1. \quad (3)$$

where \mathbf{Q}_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 is a matrix which satisfies the Frobenius-norm constraint $\|\mathbf{R}_1\|_F^2 \leq \epsilon_1^2$, for some $\epsilon_1 > 0$. Note that the model in (3) makes the reasonable assumption that \mathbf{U}_1 lies in the span of $\hat{\mathbf{V}}_1$ whose columns represent the preferred directions along which the UE wishes to receive its intended signal. In addition, the model in (3) 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.

Let us first consider UE side operations after assuming a post-scheduling model as in (3). In order to determine the SU-MIMO CSI reports the UE assumes a post-scheduling model as in (3) in which $\mathbf{U}_{\bar{1}} = \mathbf{0}$ and the matrices $\hat{\mathbf{D}}_1^{1/2}, \hat{\mathbf{V}}_1$ are equal to the diagonal matrix of the dominant unquantized singular values and the dominant unquantized right singular vectors, respectively, of its downlink channel matrix \mathbf{H}_1^\dagger . Note that models (1) and (3) are equivalent in terms of UE SU-MIMO CSI reporting. On top of SU-MIMO CSI reports, there are alternatives for configuring

the UE to report more CSI. These include the MU-CQI reporting as described in [7] as well as:

- **Enhanced CSI reporting (SU-MIMO CSI and residual error):** The UE can be configured for enhanced CSI reporting. Suppose that using SU-MIMO rules the UE determined a precoder $\hat{\mathbf{G}}_1$ of a preferred rank r_1 and the corresponding quantized SINRs $\{\hat{\text{SINR}}_1^i\}_{i=1}^{r_1}$. In order to determine the residual error, the UE assumes a post-scheduling model as in (3) in which $\hat{\mathbf{D}}_1 = \frac{r_1}{\rho_1} \text{diag}\{\hat{\text{SINR}}_1^1, \dots, \hat{\text{SINR}}_1^{r_1}\}$ and $\hat{\mathbf{V}}_1 = \hat{\mathbf{G}}_1$. Then let $\mathbf{P}_1^\perp = \mathbf{I} - \hat{\mathbf{G}}_1 \hat{\mathbf{G}}_1^\dagger$ denote the projection matrix whose range is the orthogonal complement of $\hat{\mathbf{G}}_1$. Let us refer to the matrix $\mathbf{E}_1 \triangleq \mathbf{Q}_1 \mathbf{R}_1$ as the (normalized) residual error matrix and the matrix $\mathbf{C}_1 = \mathbf{E}_1^\dagger \mathbf{E}_1$ as the residual error correlation matrix and note that $\mathbf{C}_1 = \hat{\mathbf{D}}_1^{-1/2} \mathbf{F}_1 \mathbf{H}_1^\dagger \mathbf{P}_1^\perp \mathbf{H}_1 \mathbf{F}_1^\dagger \hat{\mathbf{D}}_1^{-1/2}$. The UE can be configured to report some approximation of either the residual error matrix or the residual error correlation matrix. These include:

- Quantizing and reporting the dominant diagonal values of \mathbf{R}_1 along with the corresponding columns in \mathbf{Q}_1 .
- Quantizing and reporting the diagonal values of \mathbf{C}_1
- Quantizing and reporting only the trace of \mathbf{C}_1 , $\epsilon_1^2 = \text{tr}(\mathbf{C}_1) = \text{tr}(\mathbf{F}_1 \mathbf{H}_1^\dagger \mathbf{P}_1^\perp \mathbf{H}_1 \mathbf{F}_1^\dagger \hat{\mathbf{D}}_1^{-1})$ which can be thought of as the normalized total residual error.

Let us consider the possible eNB (a.k.a base station) side operations which involve the model in (3), i.e. at-least one of the following two cases holds true: The UE reports some CSI assuming a post-scheduling model as in (3) or the eNB assumes a post-scheduling model as in (3) for SINR approximation in the case of UE pairing.

For brevity, we illustrate one instance of how the base station can utilize the model in (3) along with the enhanced CSI UE report in which the user feedback SU CSI report along with the normalized total residual error ϵ_1^2 . Further, for simplicity let us assume that the base station considers the 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. Suppose that the UE 1 reports the SU-MIMO PMI $\hat{\mathbf{G}}_1$ of rank r_1 and CQI(s) (which are mapped to the SINRs $\{\hat{\text{SINR}}_1^1, \dots, \hat{\text{SINR}}_1^{r_1}\}$), along with the normalized total residual error ϵ_1^2 . Then using the model in (3), at the base station end we set $\hat{\mathbf{V}}_1 = \hat{\mathbf{G}}_1$ and the matrix $\hat{\mathbf{D}}_1$ to be $\frac{r_1}{\rho_1} \text{diag}\{\hat{\text{SINR}}_1^1, \dots, \hat{\text{SINR}}_1^{r_1}\}$.

Note that now \mathbf{R}_1 is not known (except for the fact that $\text{tr}(\mathbf{R}_1^\dagger \mathbf{R}_1) = \epsilon_1^2$) and \mathbf{Q}_1 is known to lie in the subspace determined by $\mathbf{I} - \hat{\mathbf{G}}_1 \hat{\mathbf{G}}_1^\dagger$. Without loss of generality, we can 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{G}_1 . To obtain a conservative SINR estimate the base station can assume that the UE employs a simple MRC receiver, i.e., user-1 is assumed to use the linear combiner $\mathbf{u}_1^\dagger \hat{\mathbf{G}}_1 \hat{\mathbf{D}}_1^{1/2}$ on the model in (3). In addition, we compute the worst-case SINR obtained by minimizing the SINR over all choices of $(M - r_1) \times r_1$ matrices \mathbf{R}_1 under the constraint that $\text{tr}(\mathbf{R}_1^\dagger \mathbf{R}_1) \leq \epsilon_1^2$. Now the worst-case SINR can be expressed as:

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

which can be simplified as

$$\frac{\|\mathbf{u}_1^\dagger \hat{\mathbf{G}}_1 \hat{\mathbf{D}}_1^{1/2}\|^4}{\|\mathbf{u}_1^\dagger \hat{\mathbf{G}}_1 \hat{\mathbf{D}}_1^{1/2}\|^2 + (|\mathbf{u}_1^\dagger \hat{\mathbf{G}}_1 \hat{\mathbf{D}}_1 \hat{\mathbf{G}}_1^\dagger \mathbf{u}_1| + \epsilon_1 \|\mathbf{u}_1^\dagger \hat{\mathbf{G}}_1 \hat{\mathbf{D}}_1\| \|\mathbf{Q}_1^\dagger \mathbf{u}_1\|)^2} \quad (5)$$

Note that in case zero-forcing (ZF) transmit precoding is used (5) further simplifies to

$$\frac{\|\mathbf{u}_1^\dagger \hat{\mathbf{G}}_1 \hat{\mathbf{D}}_1^{1/2}\|^4}{\|\mathbf{u}_1^\dagger \hat{\mathbf{G}}_1 \hat{\mathbf{D}}_1^{1/2}\|^2 + (\epsilon_1 \|\mathbf{u}_1^\dagger \hat{\mathbf{G}}_1 \hat{\mathbf{D}}_1\| \|\mathbf{u}_1\|)^2} \quad (6)$$

4 Simulation Results

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

4.1 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 MU-MIMO with SU reports for various settings are provided in Table 2. The SU-MIMO performance is also included for comparisons. The ZF transmit precoding is employed for all MU-MIMO transmissions. We can see that without applying any scheduler optimization techniques, the MU-MIMO with SU reports

Parameter	Assumption
Deployment scenario	IMT Urban Micro (UMi)
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 co-polarized ant., 0.5- λ spacing
Antenna configuration (user)	2 RX co-polarized ant., 0.5- λ spacing
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 1: Simulation Parameters

performs even worse than the SU-MIMO. With simple SINR offset to compensate for the over optimistic SU-MIMO reports, the performance is improved significantly but is still below the SU-MIMO mark. We then impose a rank restriction, i.e., $r_{\max} = 1$ on all active users via codebook subset restriction. Considering SU reporting from all users, we incorporate a user pooling in the scheduler in which only users with a good average SNR are eligible for pairing. This helps to realize the benefit of MU-MIMO with the average spectral efficiency gain being 11.5%. Then, to obtain an understanding of the gains that can be achieved via enhanced CSI reporting, we consider the case when each user reports a normalized total residual error in addition to the SU-MIMO CSI report. At the base station we modeled the post-scheduling user received output as (3) and considered the MRC SINR approximation for rate matching (6). No additional user pooling or SINR offset was applied in this case. Notice that a substantial gain of 19.7% (in terms of cell average spectral efficiency) is obtained over SU-MIMO and a gain of 8.2% is obtained over MU-MIMO with SU

MU-MIMO/SU-MIMO	cell average	5% cell-edge
SU-MIMO $r_{\max} = 2$	2.1488	0.0679
without SINR offset $r_{\max} = 2$	1.49	0.0681
SINR offset $r_{\max} = 2$	1.922	0.0698
SINR offset plus pooling $r_{\max} = 1$	2.3964 (11.5%)	0.0687 (1.2%)
MRC SINR approx. $r_{\max} = 1$	2.5722 (19.7%)	0.0834 (22.8%)

Table 2: Spectral efficiency of MU-MIMO with near orthogonal transmit precoding with zero-forcing (ZF); SU feedback or enhanced CSI feedback by the users. Relative percentage gains are over SU-MIMO.

reports.

4.2 Performance of MU-MIMO in Heterogenous Networks

We now consider a heterogenous network for which the simulation parameters are summarized in Table 3. Table 4 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 total residual error in addition to its SU-MIMO CSI report. We modeled the post-scheduling user received output as (3) and considered the MRC SINR approximation for rate matching (6). No additional user pooling or SINR offset was applied. We note that while more modest gains are obtained using residual error feedback, these gains can improve with other forms for enhanced feedback.

5 Conclusions

In this contribution, we considered enhancements to the MU-MIMO operation by enhancing the user CSI reporting and by a finer modeling of the received output seen by a user in the aftermath of scheduling. Our initial 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. Other forms for enhanced feedback that improve channel directional information are FFS.

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 3: 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	0.077
SU-MIMO Macro-cell	2.2025	0.059
SU-MIMO LPN-RRH	3.1919	0.0904
MU-MIMO Overall	3.1610 (10.4%, 5.87%)	0.0768
MU-MIMO Macro-cell	2.5365 (15.2%, 8.54%)	0.058
MU-MIMO LPN-RRH	3.4732 (8.81%, 4.92%)	0.0946

Table 4: 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.