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## 1 Introduction

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 [2–7]. 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. In order to jumpstart the discussion on MU channel state information (CSI) feedback enhancement (particularly for 4 TX), in this contribution, we summarize the gains that can be obtained by some MU-CSI feedback enhancements. More importantly, we examine a

broader framework for enhanced CSI reporting by users targeting MU-MIMO and also illustrate how the eNB can exploit such enhanced CSI feedback. Initial system level simulations indicate promising gains.

## 2 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 un-quantized 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  $\{\text{SINR}_1^i\}_{i=1}^{r_1}$  as CQIs.<sup>1</sup> 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  $\rho_1$  is the EPRE configured for the UE-1, then the effective SINR seen by the UE (after filtering using a filter  $\mathbf{F}_1$  to remove interference among columns of  $\mathbf{U}_1$ ) for the  $i^{\text{th}}$  column of  $\mathbf{U}_1$  will be  $\text{SINR}_1^i$ .

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.

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

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:

- **MU-CQI reporting:** The UE is configured to also report additional CQI computed using MU-MIMO rules and possibly an additional PMI [7]. To compute MU-CQI corresponding to a precoder  $\hat{\mathbf{G}}_1$ , the UE assumes a post-scheduling model as in (3) in which  $\hat{\mathbf{D}}_1^{1/2}, \hat{\mathbf{V}}_1$  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. It sets  $\mathbf{U}_1 = \hat{\mathbf{G}}_1$  and assumes that the columns of  $\mathbf{U}_{\bar{1}}$  are isotropically distributed in the subspace defined by  $\mathbf{I} - \hat{\mathbf{G}}_1 \hat{\mathbf{G}}_1^\dagger$  (orthogonal complement of  $\hat{\mathbf{G}}_1$ ). In addition it assumes  $\mathbf{Q}_1 = \mathbf{0}$  which is reasonable in this case since  $\hat{\mathbf{V}}_1$  is taken to contain all the unquantized dominant singular vectors so no significant interference can be received from signals in its orthogonal complement. Then, to compute MU-SINRs the UE can be configured to assume a particular number of columns in  $\mathbf{U}_{\bar{1}}$  and either an equal power per scheduled stream or a non-uniform power allocation in which a certain fraction of EPRE is shared equally among all columns of  $\mathbf{U}_{\bar{1}}$  with the remaining fraction being shared equally among all columns in  $\mathbf{U}_1$ .
- **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  $\mathbf{C}_1$ ,  $\epsilon_1^2 = \text{tr}(\mathbf{C}_1) = \text{tr}(\mathbf{F}_1 \mathbf{H}_1^\dagger \mathbf{P}_1^\perp \mathbf{H}_1 \mathbf{F}_1^\dagger \tilde{\mathbf{D}}_1^{-1})$  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  $\epsilon_1^2$ . 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  $\{\text{SINR}_1^1, \dots, \text{SINR}_1^{r_1}\}$ ), along with the normalized total residual error  $\epsilon_1^2$ . 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  $\frac{r_1}{\rho_1} \text{diag}\{\text{SINR}_1^1, \dots, \text{SINR}_1^{r_1}\}$ . 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  $\mathbf{Q}$  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

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

### 3 Simulation Results

We now evaluate the MU-MIMO performance with the different types of channel reports and the enhancement methods via system level simulations. The simulation parameters are summarized in Table 1.

#### 3.1 Performance of MU-MIMO with SU CSI Report and Enhanced CSI Report

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.

| 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., $0.5\text{-}\lambda$ spacing                               |
| Antenna configuration (user)                  | 2 RX co-polarized ant., $0.5\text{-}\lambda$ spacing                               |
| Downlink transmission scheme                  | MU-MIMO: Max 2 users/RB;<br>Each user can have rank 1 or 2                         |
| Codebook                                      | Rel. 8 codebook [?]  |
| Downlink scheduler                            | PF in time and frequency   |
| Scheduling granularity:                       | 5 RBs  |
| Feedback assumptions                          | 5ms periodicity and 4ms delay;<br>Sub-band CQI and PMI<br>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;<br>Used TBS tables in TS 36.213 [?]                    |

Table 1: Simulation Parameters

We can see that without applying any scheduler optimization techniques, the MU-MIMO with SU reports performs even worse than the SU-MIMO. With simple  $-4\text{dB}$  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

| 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. $r_{\max} = 1$         | 2.5141 (17.0%) | 0.0828 (21.9%) |

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.

base station we modeled the post-scheduling user received output as (3) and considered the MRC SINR approximation for rate matching (6). To obtain an initial result, a common value of  $\epsilon$  was used to obtain SINR approximations for any choice of pairing. The resulting the spectral efficiency of MU-MIMO is 17% better than that of SU-MIMO. This demonstrates that substantial gains can be possible via the enhanced CSI reporting and improved SINR approximation.

### 3.2 Performance of MU-MIMO with MU Report

Table 3 provides the cell average and 5% cell-edge spectral efficiencies of MU-MIMO with various CSI reporting configurations involving MU-CQI feedback. In particular, we consider the scenario when all users report PMI and CQI(s) determined using MU-MIMO rules [7]. Also, considered is a scenario in which high geometry (HG) users (whose average SNR is above a threshold) report complete MU and SU CSI reports to the base station whereas the remaining users feedback only SU CSI reports. The resulting cell spectral efficiency becomes 2.694 bit with the cost of a significant increase in the feedback signaling overhead. A more reasonable alternative is one where the SU CSI and MU CQI is obtained from HG users and the resulting the spectral efficiency is 2.6814. Note that the performance degradation compared to the full reporting by HG users is less than 0.5% and the gain over SU-MIMO is an impressive 24.8%.

| Type of reports and user pooling | Average Cell SE | 5% Cell-edge |
|----------------------------------|-----------------|--------------|
| MU report by all users           | 2.3321 (8.5%)   | 0.0734       |
| MU +SU Report by HG users        | 2.694 (25.4%)   | 0.0963       |
| SU report + MU-CQI by HG users   | 2.6814 (24.8%)  | 0.0951       |

Table 3: Spectral efficiency of MU-MIMO with near orthogonal transmit precoding with zero-forcing (ZF); Long-term SNR (Geometry) based user pooling with SU-report by low geometry users; Rank-1 codebook restriction imposed on all users. Relative percentage gains are over SU-MIMO.

## 4 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 show that such enhancements can result in substantial system throughput improvements.

## References

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