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**Agenda Item:** 6.3.2.2

**Source:** NEC Group

**Title:** Evaluation of MU-MIMO CQI/PMI Reporting Enhancement

**Document for:** Discussion and Decision

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## 1 Introduction

In the RAN-1 meeting 62-bis, a way forward on CQI/PMI reporting enhancement on PUSCH 3-1 was supported by several companies [1]. This way forward makes the following suggestions:

- In addition to Rel-8 Mode 3-1 feedback, UE can be configured via higher layer signalling to report:
  - If  $RI > 1$ , a wideband PMI (W) calculated assuming restricted rank=1; per subband CQI targeting MU-MIMO operation;
  - If  $RI = 1$  per subband CQI targeting MU-MIMO operation;
- MU-MIMO CQI is computed assuming the interfering PMIs are orthogonal to the SU-MIMO rank 1 PMI
- For 4 TX, the total number of co-scheduled layers is assumed to be 4 at the time of MU CQI computation. The 3 interfering PMIs for each SU-MIMO rank-1 PMI are listed in a table [1].
- As a baseline, uniform power allocation among the 4 layers; non-uniform power allocation FFS
- For FFS for 2 and 8-TX.

In this contribution, we provide system level simulation results to evaluate the performance offered by the different features proposed in the way forward. We highlight some key benefits of assuming 4 mutually orthogonal co-scheduled layers:

- For a eNodeB with 4 TX antennas, three orthogonal interferers span the entire complement of the signaling subspace so the particular choice of these three interferers does not matter while computing MU-SINR. Consequently, this results in a robust choice compared to MU-SINR computed based on one or two pre-specified orthogonal interferers. The latter method can result in a big mismatch whenever the pairing used by the NodeB differs (which is likely). Interestingly, assuming one or two random interferers isotropically distributed in the complement of the signaling subspace results in an SINR formula having the same form as that obtained with three orthogonal interferers [3].
- The complexity involved in computing MU-SINR remains small. In particular, for a UE with 2 RX antennas only  $2 \times 2$  matrix inverses (which can be trivially written in closed form) on top of SU-SINR computations need to be obtained. On the other hand, in case the UE has 4 or more RX antennas, the MU-SINR is just a rank-4 per-layer SINR already computed for SU-MIMO (since the 4 TX codebook is nested) so in this case there is no additional complexity over SU-MIMO CQI computation.

## 2 Simulation Results

The relevant parameters for system level simulations are detailed in Table 1. We follow the methodology for MU-MIMO system-level simulations that was agreed in [2]. This includes co-scheduling a maximum of 4 streams per time-frequency resource (a.k.a. resource block (RB)) and a maximum of 2 streams per scheduled user. Due to the extremely high complexity of optimal user scheduling, we also introduce an additional constraint in our simulations that only up-to 2 users can be co-scheduled on every RB. For all simulations, we use the 3GPP

LTE Rel. 8 codebook for PMI feedback. Moreover, we assume that each user feeds back sub-band 4 bit CQI and sub-band PMI.

Table 2 shows the average cell spectral efficiency and 5% cell edge spectral efficiency of SU-MIMO (where at-most one user is scheduled on each RB) using proportional fair scheduling.

We next consider the performance of MU-MIMO under proportional fair scheduling. First, we consider MU-MIMO in which each user employs the SU-MIMO rule to determine and report its RI, sub-band PMI and sub-band CQI(s). Recall that the CQIs computed using SU-MIMO rules are optimistic since they do not account for any post-scheduling interference. Consequently, some appropriate adjustment (optimization) must be made by the eNodeB. The result of several such optimizations, which include those described in Appendix A along with an SINR penalty prior to MCS assignment, is reported in Table 3.

We now evaluate the performance of MU-MIMO under proportional fair scheduling and different combinations of MU-plus-SU reports which include all the features proposed in the way-forward document [1]. All users are enforced to feedback only a rank-1 PMI via codebook subset restriction. Note that as per [1], no additional wideband PMI (on top of the SU-MIMO PMI(s)) is reported by the UE when the rank index RI is equal to 1. In addition, based on long-term SNR (geometry), users are divided into two categories. All users whose long-term SNR is below a threshold are always included in a *SU-MIMO pool of users* irrespective of their instantaneous channel states and hence are configured by the eNodeB to always feedback SU-MIMO reports (each consisting here of a rank-1 sub-band PMI and a sub-band CQI computed using SU-MIMO rules). Our scheduling algorithm allows scheduling users in this pool only as SU-MIMO users.<sup>1</sup> All users whose long-term SNR is above the threshold, report a combination SU-and-MU reports particular to one of the three scenarios described below. The three scenarios are described below and the results are reported in Table 4. In all scenarios, the scheduler uses the steps described in Appendix A to determine

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<sup>1</sup>We observed that such a pooling enables a good cell-edge performance along with gains in average SE.

estimates of the post-scheduling SINRs at the UEs. In each scenario, we consider two cases. The first one is where the user assumes uniform power allocation in computing its MU-CQI and the second one is where the user assumes that a fraction  $\alpha = 1/2$  of the transmit power will be used for its desired stream and the remaining fraction will be shared equally among the three mutually orthogonal interferers.

- In the first scenario, each UE whose long-term SNR is above a threshold is configured by the eNodeB to send an MU-report consisting of a sub-band MU-CQI and a sub-band rank-1 PMI, where the PMI is one which maximizes the MU-CQI over all rank-1 vectors in the codebook. We remark that since no SU-CQI is available from such a UE, the scheduler adds an additional positive sub-band SINR offset prior to MCS assignment whenever such a UE is scheduled alone on that sub-band.
- In the second scenario, each UE whose long-term SNR is above a threshold is configured by the eNodeB to send an MU-report (as in the first scenario) along with a sub-band SU-CQI which is computed using the PMI for that sub-band contained in the MU-report. We remark that now the sub-band SU-CQI is available for the scheduler to use whenever such a UE is scheduled alone on a sub-band.
- In the third scenario, each UE whose long-term SNR is above a threshold is configured by the eNodeB to send an SU-report (consisting of a sub-band CQI and a sub-band rank-1 PMI computed using SU-MIMO rule) along with a sub-band MU-CQI which is computed using the PMI for that sub-band contained in the SU-report. This scenario is aligned with the way forward [1] and hence is highlighted.

The results are reported in Table 5 which considers an eNB with closely spaced cross-polarized antennas. We remark that the gains reported for all cases that employ MU-CQI are pessimistic since they do not allow for dynamic rank adaptation by the UE. Enabling such dynamic rank adaptation should allow even more gains to be obtained using the WF proposal [1].

Parameter	Assumption
Deployment scenario	IMT Urban Micro (UMi)
Duplex method and bandwidth	FDD: 10MHz for downlink
Network synchronization	Synchronized
Antenna configuration (eNB)	4 TX co-pol antennas with 0.5-lambda spacing
Antenna configuration (UE)	2 RX co-pol antennas with 0.5-lambda spacing
Cell layout	Hexagonal grid 19 sites, 3 cells per site
Number of UEs per sector	10
Downlink transmission scheme	MU-MIMO: Max 2 co-scheduled UEs per RB.
	Each UE can have rank-1 or rank-2
Codebook	Rel.8 codebook
Downlink scheduler	Proportional fair in time and frequency
Feedback assumptions	Report is with 5ms periodicity and 4ms delay
	Sub-band CQI and PMI without errors.
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 3GPP TS 36.213 for throughput calculation.

Table 1: Simulation Parameters

SU-MIMO	Average Cell SE	5% Cell Edge SE
PF	2.0426	0.0688

Table 2: Spectral efficiency ((SE) in bits/s/Hz) performance of SU-MIMO with SU-report including RI, sub-band PMI, sub-band CQI feedback

### 3 Conclusions

In this contribution, we considered enhancements to the MU-MIMO operation which aim to reduce the mismatch between the user reported SINRs and the ones it actually observes in the aftermath of scheduling. Our results show that obtaining MU-CQI from a subset of users can result in substantial system throughput improvements. Further, a robust choice of MU-CQI for 4 TX is one that is computed assuming a fraction  $\alpha = 1/2$  of the transmit

<b>MU-MIMO, SU-Report</b>	<b>Average Cell SE</b>	<b>5% Cell Edge SE</b>
PF	2.3829	0.0822

Table 3: Spectral efficiency ((SE) in bits/s/Hz) performance of MU-MIMO with SU report and near orthogonal transmit precoding with zero-forcing (ZF)

<b>MU-MIMO</b>	<b>Average SE</b>	<b>5% SE</b>
PF; MU report by high geometry users	2.5232 (5.8%)	0.0879 (6.9%)
PF; MU report by high geometry users $\alpha = 1/2$	2.5972 (8.9%)	0.0885 (7.6%)
PF; MU + SU-CQI report by high geometry users	2.5765 (8.1%)	0.0925 (12.5%)
PF; MU + SU-CQI report by high geometry users $\alpha = 1/2$	2.6098 (9.5%)	0.0888 (8.0%)
PF; <b>MU-CQI + SU report by high geometry users</b>	2.5642 ( 7.6%)	0.0923 (12.2 %)
PF; <b>MU-CQI + SU report by high geometry users</b> $\alpha = 1/2$	2.5984 (9.0 %)	0.0905 (10 %)

Table 4: Spectral efficiency ((SE) in bits/s/Hz) performance 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 MU-MIMO with SU-reports.

power will be used for its desired stream and the remaining fraction will be shared equally among the three mutually orthogonal interferers.

MU-MIMO	Average SE	5% SE
PF; SU-report	2.54	0.078
PF; MU-CQI + SU report by high geometry users	2.643 (4%)	0.077
PF; MU-CQI + SU report by high geometry users $\alpha = 1/2$	2.65 (4.3 %)	0.082

Table 5:  $4 \times 2$  cross-polarized  $1/2\lambda$ . Spectral efficiency ((SE) in bits/s/Hz) performance of MU-MIMO with near orthogonal transmit precoding with zero-forcing (ZF); For MU-CQI reporting: long-term SNR (Geometry) based user pooling with SU-only report by low geometry users and Rank-1 codebook restriction imposed on all users.. Relative percentage gains are over MU-MIMO with SU-reports.

## Appendix A Scheduling at the Base station

The eNB receives PMIs and associated CQIs from all active users. Among the many possible choices, it then has to select a suitable set of users, determine their associated transmit precoders and assign rates to them. In order to do so, the eNB must be able to compute an estimate of the SINR for each co-scheduled stream in each choice of user set and associated transmit precoders. We note that [4, 5] originally suggested methods for computing such an estimate.

In this section we describe the method we employed. Note that the method proposed below allows the eNB to co-schedule an arbitrary number of streams (not necessarily equal to the value 4 that is assumed by the users while evaluating the MU-CQI as per [1]) along arbitrary transmit precoders. In particular, suppose that the eNB considers co-scheduling  $Q$  users, say user-1 to user- $Q$ , who have reported precoders  $\{\hat{\mathbf{G}}_j\}_{j=1}^Q$ , respectively. Also assume all users employ linear MMSE receivers and let  $\mathbf{H}_1^\dagger$  to  $\mathbf{H}_Q^\dagger$  denote the channels seen by users 1 to  $Q$ , respectively. Let  $\mathbf{V}_j = [\mathbf{v}_j^1, \dots, \mathbf{v}_j^{r_j}]$  denote the  $M \times r_j$  transmit precoder (of rank  $r_j$  and with unit-norm columns) that the eNB intends to employ for user  $j$ ,  $1 \leq j \leq Q$  such that  $R' = \sum_{j=1}^Q r_j \leq M$ . Define  $\mathbf{A} = [\mathbf{V}_1, \mathbf{V}_2, \dots, \mathbf{V}_Q]$ . Using standard formulas it can be verified that the *true SINR* seen by user- $j$  for its  $i^{th}$  stream that is transmitted along  $\mathbf{v}_j^i$  is given by

$$\text{sinr}_j^i = \hat{\rho} \mathbf{v}_j^{i\dagger} \mathbf{H}_j (\mathbf{I} + \hat{\rho} \mathbf{H}_j^\dagger (\mathbf{A} \mathbf{A}^\dagger - \mathbf{v}_j^i \mathbf{v}_j^{i\dagger}) \mathbf{H}_j)^{-1} \mathbf{H}_j^\dagger \mathbf{v}_j^i, \quad (1)$$

where  $\hat{\rho} = \rho/R'$  is the power per stream. Then, the following simple but useful lemma provides an alternate expression for the SINR given in (1).

**Lemma 1** *The true SINR seen by user- $j$  for its  $i^{\text{th}}$  stream is equal to*

$$\begin{aligned} \text{sinr}_j^i &= \frac{\alpha_j^i}{1 - \alpha_j^i}, \\ \alpha_j^i &= [(\mathbf{I} + \mathbf{A}^\dagger \mathbf{R}_j \mathbf{A})^{-1} \mathbf{A}^\dagger \mathbf{R}_j \mathbf{A}]_{\sum_{m=1}^{j-1} r_m + i, \sum_{m=1}^{j-1} r_m + i}, \end{aligned} \quad (2)$$

for all  $i = \{1, \dots, r_j\}$  and where  $\mathbf{R}_j = \hat{\rho} \mathbf{H}_j \mathbf{H}_j^\dagger$ .

An important consequence of (2) is that the BS can approximate the matrix  $\mathbf{R}_j$  by  $\hat{\mathbf{R}}_j$  and then determine approximate SINRs as

$$\begin{aligned} \hat{\text{sinr}}_j^i &= \frac{\hat{\alpha}_j^i}{1 - \hat{\alpha}_j^i}, \\ \hat{\alpha}_j^i &= [(\mathbf{I} + \mathbf{A}^\dagger \hat{\mathbf{R}}_j \mathbf{A})^{-1} \mathbf{A}^\dagger \hat{\mathbf{R}}_j \mathbf{A}]_{\sum_{m=1}^{j-1} r_m + i, \sum_{m=1}^{j-1} r_m + i}. \end{aligned} \quad (3)$$

Here we employ the following approximation

$$\mathbf{R}_j \approx \hat{\mathbf{R}}_j \triangleq \hat{\mathbf{G}}_j \hat{\mathbf{D}}_j \hat{\mathbf{G}}_j^\dagger, \quad \forall j, \quad (4)$$

where  $\hat{\mathbf{D}}_j = \text{diag}\{\gamma_j \text{SINR}_j^1, \dots, \gamma_j \text{SINR}_j^{r'_j}\}$  and  $r'_j \geq 1$  is the rank of  $\hat{\mathbf{G}}_j$ .  $\{\text{SINR}_j^i\}$  are the SINRs reported by user  $j$ .  $\gamma_j$  is a scaling factor such that  $\gamma_j = 4/R'$  if user  $j$  determines MU-CQI assuming 4 co-scheduled streams and  $\gamma_j = r'_j/R'$  when the user employs the SU-MIMO rule instead. A few comments on this approximation are in order.

**Remark 1** *Note that the approximation in (4) attempts to obtain the best rank  $r'_j$  approximation of  $\mathbf{R}_j$  based on the feedback of user- $j$ . Clearly the best rank  $r'_j$  approximation of  $\mathbf{R}_j$  is the matrix formed when  $\hat{\mathbf{G}}_j$  contains the  $r'_j$  dominant eigenvectors of  $\mathbf{R}_j$  and  $\hat{\mathbf{D}}_j$  contains the  $r'_j$  dominant eigenvalues. It can be verified that  $\hat{\mathbf{R}}_j$  approaches  $\mathbf{R}_j$  as the codebook and quantization resolution improve. Note however, that even under the best rank  $r'_j$*

approximation of  $\mathbf{R}_j$ ,  $\hat{\text{sinr}}_j^i$  can be different from  $\text{sinr}_j^i$  if  $r'_j < \text{Rank}(\mathbf{R}_j)$ .

**Remark 2** Under the approximation in (4) and (2), user- $j$  sees no interference from co-scheduled user- $q$  if  $\hat{\mathbf{G}}_j^\dagger \mathbf{V}_q = \mathbf{0}$ .

## References

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