A MU-MIMO CQI estimation method for MU-MIMO UEs in LTE systems

Hung Tuan Nguyen*, Istvan Z. Kovacs†
* Department of Electronic Systems, Aalborg University, Denmark,
Email:htn@es.aau.dk
† Nokia Siemens Networks Aalborg-DK

***Abstract*—This paper addresses a method to estimate the multi user channel quality indicator (CQI) from the reported rank 1 single user CQI in LTE systems. We investigate the relationship between the multi user CQI and the channel condition. Based on that, we propose an updating mechanism where the estimated multi user CQI is varied according to the reported channel condition i.e. the rank 1 single user CQI. System performance of the proposed scheme is compared with the conventional fixed offset single user CQI estimation. System level simulation results show the efficiency of our proposed scheme with respect to both the enhancement in the system level performance and uplink overhead reduction. Using the statistic metrics derived from the system level simulation, we highlight the importance of having an accurate multi user CQI estimation. The results illustrate how the multi user CQI information influence the packet scheduling and link adaptation decisions and ultimately the overall system performance.**

I. Introduction

Being able to utilize the spatial dimensions or multi user diversity of the multiple input multiple output (MIMO) channels, multi user MIMO (MU-MIMO) transmission appears to be a preferred transmission scheme in certain scenarios for example when the number of transmit antennas is higher than that of the receive antennas or when the fading channels among antennas are correlated. In these conditions, the additional degree of freedom i.e. multi user diversity can help to improve the performance of the MU-MIMO system as compared to the single user MIMO (SU-MIMO) system. The gain of the downlink MU-MIMO system over SU-MIMO system have been extensively investigated in theory. Most of the studies concentrate on designing an optimal precoding with linear and non-linear processing [1]-[4]. They often start with the assumption that the base station has perfect knowledge of the MU-MIMO channel.

Due to the advantage of MU-MIMO, 3GPP Release 8 Long-Term Evolution (LTE) has defined a transmission mode for downlink MU-MIMO transmission, besides the transmission mode SU-MIMO transmission with rank adaptation, [11]. Both of the modes use a predefined codebook and the user equipment (UE) needs to report its preferred precoder and the corresponding Channel Quality Indicator (CQI) to the evolved Node B (eNB). In order to reduce the feedback overhead and the computing complexity, it has been decided to apply the same precoder selection mechanism in SU-MIMO to MU-MIMO, [11]. Moreover, in MU-MIMO transmission, as the UE is not aware of the other multiplexed UE, the CQI information at the eNB is limited to rank 1 SU-MIMO CQI only. It is up to the eNB to estimate the MU-MIMO CQI for scheduling and link adaptation purposes. Therefore, it is a challenging task to obtain a reasonably accurate MU-MIMO CQI estimation from the reported rank 1 SU-MIMO CQI. Failing to accurately estimate the MU-MIMO CQI could lead to a wrong packet scheduling (PS) and link adaptation (LA) decisions. The system performance could incur degradation as a result.

Most of the current MU-MIMO CQI estimations in downlink LTE system adapt a fixed offset to the reported rank 1 SU-MIMO CQI. The power sharing and the multi user interference (MUI) factors are considered when calculating the offset values [6]. The power sharing is applied to make sure that the transmit power per physical resource block (PRB) is the same in either MU-MIMO transmission mode or SU-MIMO transmission mode. Multiplexing multiple data streams per PRB would results in leakage among the streams if the transmissions are not totally orthogonal. Therefore, it is inherent that, MU-MIMO CQI is inferior to the rank 1 SU-MIMO CQI also due to the MUI level. Although this method has an advantage due to its simplicity, the fixed offset level might not be optimal for the whole range of rank 1 SU-MIMO CQI values. Recently in [7], a simulation based method for estimating the MU-MIMO CQI from rank 1 SU-MIMO CQI was proposed. Because the results were derived based on simulations, the relationship between the rank 1 SU-MIMO CQI and MU-MIMO CQI was presented in form of a lookup table and no detail investigation on the relationship between these two CQI values was given. In this paper we investigate how the MU-MIMO CQI differs from the feedback rank 1 SU-MIMO CQI at different channel conditions. The relationship between the rank 1 SU-MIMO CQI and the MU-MIMO CQI is generalized and a closed form estimation is derived. Based on that, we propose an adaptive MU-MIMO CQI estimation scheme whereby the channel condition of the UE is taken into account when the MU-MIMO CQI is updated. The efficiency of the scheme is verified by mean of system level simulations.

The paper is organized as follows. In Section II, we describe the current and our proposed schemes for estimating MU-MIMO CQI from the reported rank 1 SU-MIMO CQI. The system level simulation assumptions and settings are presented in Section III. The performance gain of our proposed CQI estimation scheme as compared to the conventional scheme is

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illustrated in Section IV. The paper ends in Section V with conclusions and remarks.

II. Method for estimating MU-MIMO CQI from the reported Rank 1 SU-MIMO CQI

For rank 1 transmission the UEs estimate the CQI based on the received signal power of the reference symbols and the estimate inter-cell interference plus additive white Gaussian noise (AWGN). The rank 1 SU-MIMO CQI can be estimated as follows:

$$CQI_{SU-MIMO} = \frac{S}{I + N_{AWGN}} \tag{1}$$

where S is the average received signal power including the precoder over a subband, I is the average inter-cell interference power modeled as full inter-cell interference with rank 1 transmission and N_{AWGN} is the AWGN. It should be noted here that in this work the CQI is referred to the signal to noise plus interference ratio (SINR) value and not to the modulation and coding scheme (MCS) index.

At the eNB, an estimation of the MU-MIMO CQI is needed for the PS and LA purposes. Better MU-CQI estimation means better PS and LA decisions which improves the MU-MIMO transmission performance.

1) Conventional MU-MIMO CQI estimation scheme: Currently a fixed offset value is often used to estimate the MU-MIMO CQI from the rank 1 SU-MIMO CQI [6]. The advantage of this scheme lies in its simplicity. Further more, as the estimation is based on the existing feedback information, no additional feedback overhead is required. The offset value, Δ_{Offset} consists of two parts. The first part accounts for the power sharing when N MU-MIMO UEs share the same PRB. The second part is the estimated multi user interference (MUI).

$$CQI_{MU-MIMO} = CQI_{SU-MIMO} - \Delta_{Offset} \tag{2}$$

2) Proposed adaptive MU-MIMO CQI estimation scheme: The implementation of the fixed offset scheme presented in Section II-1 is very simple. However, it may be optimal only for a certain CQI range. In the follows, we investigate in detail how the MU-MIMO CQI is established and propose our MU-MIMO CQI estimation scheme. When the UEs in MU-MIMO mode, due to the power sharing the transmitted power intended for each UEs is reduced by $1/N$ (N is the number of multiplexed UEs per PRB) as compared to the case when it is in SU-MIMO transmission mode. The MU-MIMO UEs have the same inter-cell interference and AWGN power level as it is in SU-MIMO transmission mode. However, as they are multiplexed over one PRB, there is an additional MUI term. The estimated MU-MIMO CQI can be calculated as follows

$$CQI_{MU-MIMO} = \frac{S/N}{N_{AWGN} + I + MUI} \tag{3}$$

The MUI level is dependent on the precoders of the multiplexed MU-MIMO UEs, the fading channel and the receiver type. With a good precoders design e.g. each one is in the null space of the other and good receiver design e.g. being able to cancel all the interference the MUI level can be reduced to a negligible level as compared to the inter-cell interference plus AWGN. However, in practice, due to the limitations in the feedback of the channel state information (CSI), e.g. feedback delay, quantization and channel estimation errors, one can not completely remove the MUI. Because the MUI stems from the signals of the $(N-1)$ other multiplexed UEs, the relation between the MUI and the transmit power level can be described as

$$MUI = \Delta_{MUI} \frac{(N-1) * S}{N} \tag{4}$$

where Δ_{MUI} is a factor indicating how well the MUI was reduced. For a perfect receiver and precoder, Δ_{MUI} is equal to zero. When Δ_{MUI} is 1, we have a very bad receiver and/or precoders which can not reduce any amount of MUI. To give an idea on the range of Δ_{MUI}, we collected the Δ_{MUI} values by means of simulations. In Figure 2 we show the distribution of Δ_{MUI} for a particular 4x2 MU-MIMO system with N=2 multiplexed MU-MIMO UEs, using LTE-Release 8 codebook and Linear Minimum Mean Square Error (LMMSE) receivers. The mean value of Δ_{MUI} is in the order of 0.05. A little higher value was found for the case of 2x2 MU-MIMO with LTE-Release 8 and LMMSE receiver.

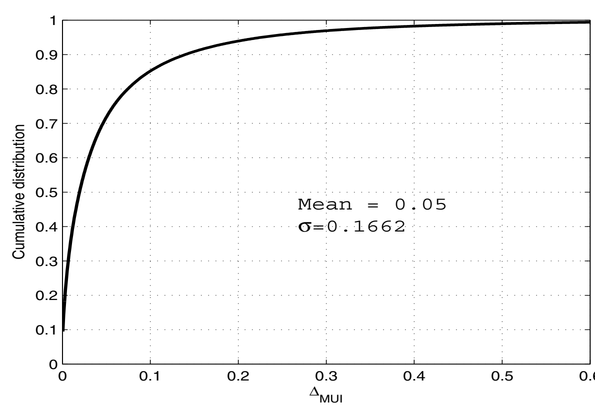

Fig. 1. Distribution of Δ_{MUI} for 4x2 MU-MIMO using LTE-Release 8 codebook and LMMSE receiver

Applying (4) into (3), the MU-MIMO CQI can be estimated from the rank 1 SU-MIMO CQI in (1) as follows

$$CQI_{MU-MIMO} = \frac{1}{\frac{N}{CQI_{SU-MIMO}} + \Delta_{MUI}(N-1)} \tag{5}$$

From (5) it can be seen that the MU-MIMO CQI is dependent on the rank 1 SU-MIMO CQI which is more complex than (2). The difference between these two CQI values is not just a simple offset value. Figure 2 illustrates the relation between the MU-MIMO CQI and the rank 1 SU-MIMO CQI as described in (5) with different Δ_{MUI} values and $N = 2$ UEs per PRB. When the rank 1 SU-MIMO CQI value is small, the MUI term is close to zero and the power sharing effect is dominating. As the rank 1 SU-MIMO CQI value increases, the

MUI term is dominating and the MU-MIMO CQI gradually reduces. At very high rank 1 SU-MIMO CQI values and for $\Delta_{MUI} > 0$, the MU-MIMO CQI starts to saturate and reaches a saturated point of

$$CQI^{Saturated}_{MU-MIMO} = \frac{1}{(N-1)\Delta_{MUI}} \tag{6}$$

In the same Figure 2 we also plot the MU-MIMO CQI using the conventional estimation method with a fixed offset value of -4.7 dB, [6]. This offset value was found to be a reasonable number to obtain a good system level performance. The detail information on the selected CQI offset value and the corresponding system level simulations are presented in Section III and Section IV.

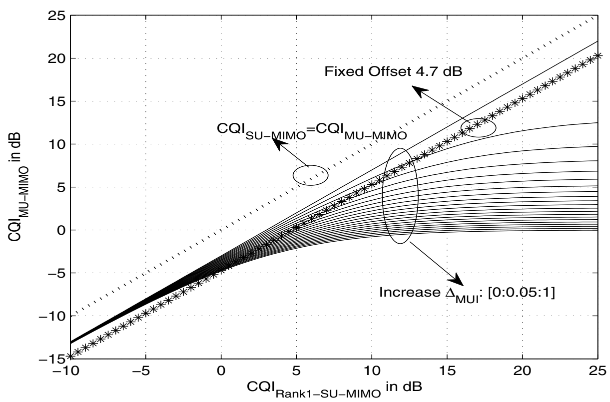

Fig. 2. Estimation of the MU-MIMO CQI from the Rank1 SU-MIMO CQI as the function of the MUI factor Δ_{MUI}

A noticeable mismatch between the fixed offset MU-MIMO CQI estimation scheme and our proposed adaptive MU-MIMO CQI estimation scheme occurs at high SU-MIMO CQI range. For a typical LMMSE receiver with Δ_{MUI}=0.05, the biggest difference in the two estimated CQI values is in the order of 10dB. In general, at high rank 1 SU-MIMO CQI region the fixed offset CQI schemes seems to over-estimate the MU-MIMO CQI. It should be noted here that, by extensive system level simulations, a relationship between the rank 1 SU-MIMO CQI and the estimated MU-MIMO CQI in form of a look up table for a particular 4x2 MU-MIMO system has been already reported in [7]. Although there is a lack of explanation for the variation of the estimated MU-MIMO CQI with the rank 1 SU-MIMO CQI, the reported results are similar to our estimation presented in (5) with Δ_{MUI}=0.05, Figure 1.

III. Simulation methodology and assumptions

Together with the conventional fixed offset CQI estimation, the proposed MU-MIMO CQI estimation schemes is implemented in a downlink multi-cell system level simulator. A LTE-Release 8 4x2 MU-MIMO system was selected for a case study. To comply with the LTE-Release 8 specification, the CSI feedback scheme with per subband CQI and wideband PMI was selected. As MU-MIMO system can obtain the best performance when the transmitting antennas are correlated [12], in the simulations we considered only the correlated and highly correlated transmitting antennas scenarios. A backoff value of -4.7 dB, as in [6], was selected for the fixed offset MU-MIMO CQI estimation scheme. This means 3 dB for the power sharing of 2 multiplexed MU-MIMO UEs per PRB and 1.7 dB for MUI. This offset value is optimized by numerous system level simulations conditioning on both the number of UEs scheduled in MU-MIMO mode and the overall system performance. The major input parameters for the simulations are shown in table I.

TABLE I
Basic system parameters used in the simulations

Parameters	Setting
Test Scenario	3GPP Macro cell case 1, 19 sites, 57 cells with 3 center cells simulated, 20 drops
Number of UEs	20 UEs per cell
Simulated bandwith	10 Mhz bandwidth centered at 2 GHz
CQI/PMI group size	1 CQI per 3 PRBs and wideband PMI
CQI estimation error	Log normal with 1 dB std
CQI reporting resolution	4 bits
CQI, PMI reporting time/delay	10/6 TTIs
Packet scheduling	Proportional fair in time and frequency domain
1st BLER target	10%
Tx and Rx	4x2 MIMO with SU and MU transmissions
Tx Correlation	Semi-Correlated with 0.5 λ Tx antennas separation and 8^o azimuth spread Highly Correlated with 0.5 λ Tx antennas separation and 5^o azimuth spread
MU-MIMO precoding	SU-MIMO LTE-Rel'8 Unitary precoder
Receiver structure	Interference Rejection Combining (IRC) for Rank 1 SU-MIMO UEs and LMMSE for MU-MIMO UEs and Rank 2 SU-MIMO
MU-MIMO configuration	N=2 multiplexed UEs per PRB
T_{min}	64 kbps
MUI suppression factor	Fixed to the mean value Δ_{MUI}=0.05, Fig. 1

To provide further information on how the proposed MU-MIMO CQI is used in the radio resource management unit at the eNB, in the following we briefly describe the working mechanism of the packet scheduler for SU-MIMO and MU-MIMO transmissions. More detail on the MU-MIMO packet scheduling can be found in [10]. The packet scheduler for SU-MIMO transmission is often carried out in two phases: time domain packet scheduler (TDPS) and frequency domain packet scheduler (FDPS). An overview of this TD-FD packet scheduling framework in downlink LTE system can be found e.g. in [8] and [9]. When MU-MIMO transmission scheme is configured, the UE can be scheduled in SU-MIMO (Rank 1) mode or MU-MIMO mode depending on whether the multi-user UE pairing condition(s) is met or not. For the pairing purpose, the UEs are classified into primary UEs and MU candidate UEs. To comply as much as possible with the SU-MIMO mode, the primary UEs are defined as the UEs scheduled for transmission using the same SU-MIMO packet scheduling mechanism. The candidate UEs are all UEs with the first Hybrid Automatic Repeat Request (HARQ) transmission. This means UEs with retransmission will not be selected as the candidate UEs. For each PRB, from the list of candidate UEs we try to find the best UE to multiplex with the primary UE. The criterion for selection is that the candidate UE should have an assigned precoder orthogonal to that of the primary UE. This condition is applied to make sure that the UEs would not cause too much MUI to each other. To avoid scheduling the UEs at the cell-edge into MU-MIMO mode, the predicted throughput of both the primary UE and the candidate UEs on the considered PRB should be larger than a threshold $Tmin$. The third requirement is that the candidate UE together with the primary UE should have the sum PF (Proportional Fair) metrics in MU mode larger than that of the primary UE in SU mode. The PF metrics in MU mode are calculated based on the estimated MU-MIMO CQI and the past user throughput. Normally we have a list of candidate UEs those meet these requirements. From this list, the candidate UE that has the highest PF metric in MU mode will finally be paired with the primary UE and set to MU transmission mode. If none of the candidate UE meets these three requirements, the primary UE will transmit in Rank 1 SU-MIMO mode as normal. After the transmission mode for each UE at each PRB is decided the LA unit will assign the modulation and MCS for each scheduled UE. The assignment of the MCS is based on the rank 1 SU-MIMO CQI for SU-MIMO UEs and the estimated MU-MIMO CQI for MU-MIMO UEs). The MCS which provides the highest throughput is selected as long as the corresponding block error rate (BLER) is still lower than the target BLER.

From the above described MU-MIMO PS mechanism we can see that the MU-MIMO CQI is a very important factor for a correct packet scheduling and MCS assignment. Incorrect estimation of the MU-MIMO CQI leads to sup-optimal and sometimes incorrect scheduling decisions.

IV. System level performance

Figure 3 shows the distribution of the user throughput for the SU-MIMO system, MU-MIMO system with fixed offset CQI estimation and MU-MIMO system with our proposed adaptive CQI estimation. In general, the user throughput of the MU-MIMO system with adaptive CQI estimation outperforms that of the system with fixed offset CQI estimation. The conclusion is valid for both correlated and highly correlated transmitting antenna cases. Our proposed adaptive CQI estimation scheme performs slightly better when the transmitting antennas are more correlated.

Figure 4 illustrates the average cell throughput of the SU-MIMO system and MU-MIMO system with different MU-MIMO CQI estimation schemes. Again, we can see that our proposed MU-MIMO CQI estimation scheme provides a better performance than the fixed offset estimation scheme. For both transmitting antenna correlation cases, an increase in the average cell throughput of around 8% can be obtained.

To provide further understanding on the gain mechanisms of our proposed scheme as compared to the fixed offset MU-MIMO CQI estimation scheme, we plot in Figure 5 the BLER

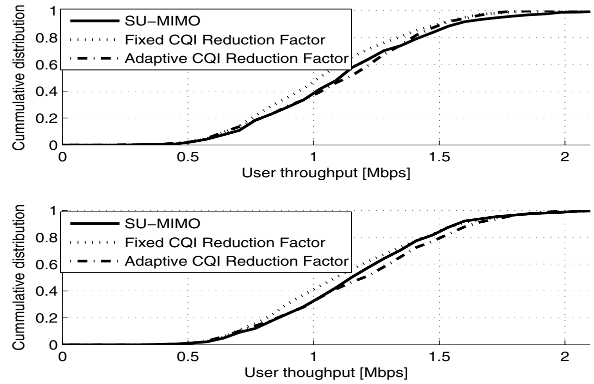

Fig. 3. Distribution of the UE throughput for SU-MIMO and MU-MIMO with fixed offset CQI and adaptive CQI estimation, correlated Tx (first row) and highly correlated Tx (second row)

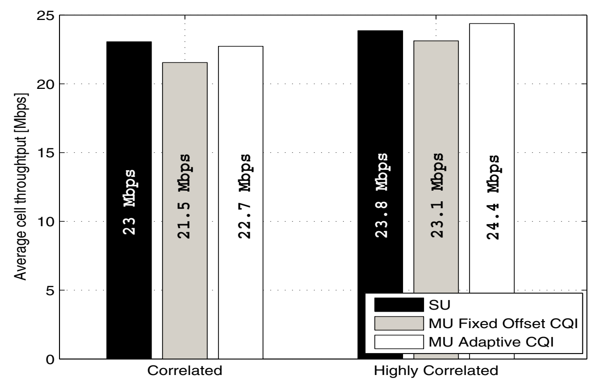

Fig. 4. Average cell throughput for SU-MIMO and MU-MIMO with fixed offset CQI and adaptive CQI estimation

at different HARQ transmissions. It can be seen that, there is more error at the first transmission for the system applying fixed offset CQI estimation scheme. While the MU-MIMO system applying our proposed scheme gives almost the same BLER at the first transmission as the SU-MIMO system. This indicates the fact that with a better estimation of the MU-MIMO CQI, our propose scheme makes it possible for the LA to work more efficient. Whereby, the MCS that matches with the channel condition can be correctly allocated.

Although the outer loop link adaptation (OLLA) [13], [14] can help to adjust the estimated CQI and thereby the MCS for SU-MIMO in general and MU-MIMO in particular, it takes some time for the procedure to convert. Therefore, the mismatch between the estimated MU-MIMO CQI and the true" CQI could still significantly degrade the system performance. Basically, the OLLA will adjust the estimated CQI (either it is SU-MIMO CQI or MU-MIMO CQI) based on the Acknowledge/Not Acknowledge (ACK/NACK) feedback. If there are too many ACKs, the OLLA will increase the estimated CQI by a certain amount so that a better MCS can be assigned to the UE. On the other hand, if there are too many

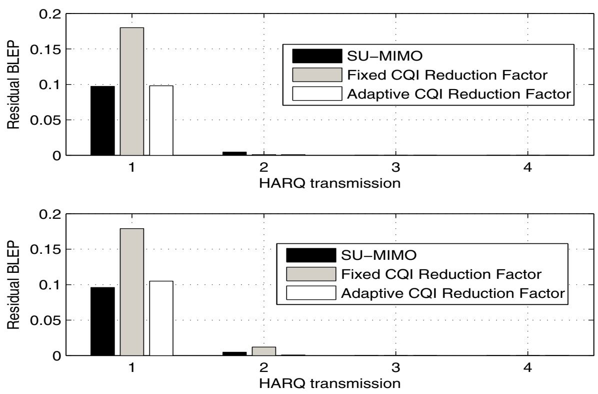

Fig. 5. Residual BLEP at difference HARQ transmission for SU-MIMO and MU-MIMO with fixed offset CQI and adaptive CQI estimation, correlated Tx (first row) and highly correlated Tx (second row)

NACKs, meaning the CQI is over-estimated, the OLLA will accordingly reduce the estimated CQI. Therefore, by looking at the distribution of the OLLA offset we can also justify how well the CQI estimation performs. Figure 6 shows the distribution of the OLLA offset for MU-MIMO with the fixed offset CQI estimation scheme and our proposed adaptive MU-MIMO CQI estimation scheme. The OLLA offset distribution of the SU-MIMO system is also shown as a reference. We can see that the OLLA offset distributions of both the SU-MIMO system and the MU-MIMO system with adaptive CQI estimation scheme show the same trend with almost negligible differences. On the contrary, the OLLA offset distribution of the system with fixed offset MU-MIMO CQI estimation is more biased to the positive side. This means the MU-MIMO CQI is systematically over-estimated and most of the cases the OLLA has to adjust the CQI by this biased values.

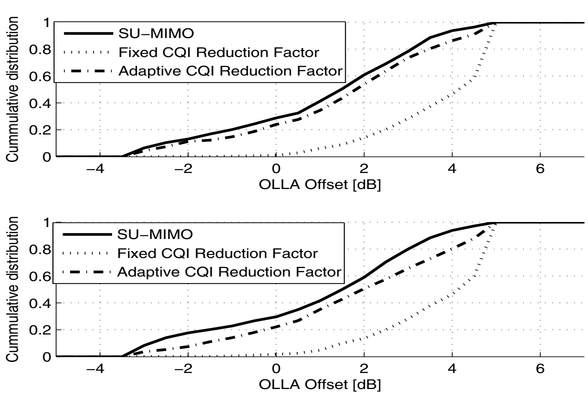

Fig. 6. Distribution of the OLLA offset for SU-MIMO and MU-MIMO with fixed offset CQI and adaptive CQI estimation, correlated Tx (first row) and highly correlated Tx (second row)

V. Conclusion and Remarks

In this paper we have proposed a method to improve estimation of the MU-MIMO CQI based on the reported rank 1 SU-MIMO CQI. The performance of the proposed scheme is evaluated by system level simulations with a LTE-Release 8 4x2 MU-MIMO system as a study case. The simulation results show that our proposed scheme outperforms the conventional fixed offset MU-MIMO CQI estimation scheme. With the proposed scheme, a gain in the order of 8% in the average cell throughput can be obtained. It is shown that the gain is obtained by having a better MU-MIMO CQI estimation and therefore better multi-user packet scheduling and link adaptation decisions.

Although only codebook based system is selected to show the performance enhancement, our proposed scheme can work well for non-codebook based (zero forcing precoder) systems which are expected to be introduced in LTE-Advanced. Besides, from a system level perspective, the Δ_{MUI} factor can be made adaptive using the same mechanism in the OLLA method [13], [14]. The idea is first to use a default Δ_{MUI} value and then adjust it according to the ACK/NACK information reported by UEs scheduled in MU-MIMO mode. In this way, each UE will have its own optimum Δ_{MUI} value where its MUI reduction capability is embedded. It is also one of the topics for future work where we are planning to evaluate the performance of the scheme with adaptive Δ_{MUI} on top of the advanced features for MU-MIMO in LTE-Advanced.

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