Analysis of CQI prediction for MU-MIMO in LTE Systems

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***Abstract*—The aim of this paper is to get an insight of multi-user multiple-input and multiple-output (MU-MIMO) channel quality indicator (CQI) prediction for long term evolution (LTE) systems. MU-MIMO CQI predictions have been investigated for LTE Release 8 (rank one, Transmission Mode 5) and for LTE Release 9 (adaptive rank, Transmission Mode 8) at the link level. The relationship between CQI reporting and channel conditions is analytically analysed and demonstrated. The tradeoff between the performance gain and the feedback overhead w.r.t. MU-MIMO CQI prediction is investigated as well. The results have shown how MU-MIMO CQI prediction is influenced by channel correlation and that significant improvements can be achieved through rank adaption and receiver choice. The results have also shown the potentially most efficient system configuration (feedback design and CQI prediction scheme) to facilitate MU-MIMO transmission for practical LTE systems.**

I. Introduction

Multi-user Multiple-Input and Multiple-Output (MU-MIMO) systems have became promising in the context of achieving high data rates required for cellular standards after 3rd Generation (3G) of wireless systems. MU-MIMO is supported in 3GPP Long Term Evolution (LTE) Rel-8 to Rel-10 with codebook feedback based precoding for up to eight transmit antennas [1]-[3]. In MU-MIMO, the UE estimates the downlink channel based on pilot symbols and inform the basis station (eNodeB) on the preferred transmit precoding vector via precoding matrix index (PMI) feedback. Then, the UE calculates the related Channel Quality Indicator (CQI) based on the post-processing signal to interference ratio (SINR). In eNodeB, the best simultaneous user pairs based on the reported PMI and the related CQIs are selected.

In order to keep low feedback overhead, it has been agreed in 3GPP that the same codebook optimised for single-user MIMO (SU-MIMO) is applied in MU-MIMO [1]. Therefore, the selection of PMI and CQI for MU-MIMO is limited to SU-MIMO feedback. This suboptimal PMI selection and CQI reporting limit the gains of multi-user transmission. Failing to accurately estimate MU-MIMO CQI can lead to to wrong packet scheduling and link adaption and thus overall performance degradation.

CQI prediction schemes for code-book based MU-MIMO have been investigated in [4]-[6]. The principle of these schemes is to predict the proper user specific (UE)-specific CQI for MU-MIMO transmission based on the UE reported SU-MIMO PMI/CQI. These predicted MU-MIMO CQI facilitate accurate link adaption and keep best quality of service (QoS) requirement of the connection to each UE. Two conventional CQI update schemes, namely closed-form metric method and fixed backoff method, are summarized in [4] together with a proposed new scheme. The new scheme in [4] utilizes the statistical distribution of MU-MIMO CQI with given SU-MIMO CQI in the manner of offline simulations and generates a look up table (LUT) of transferring CQIs with a certain criterion, e.g. minimum QoS. In [5], an enhanced LUT with quantized differential CQI feedback scheme is introduced for MU-MIMO CQI prediction with multi-level dynamic backoff. In [6], CQI update methods for both codebook and zero-forcing (ZF) based precoding schemes are proposed.

In this paper we analyse two different MU-MIMO CQI prediction schemes for LTE systems with different releases and different precoding schemes, focus on the link level system performance in terms of throughput and channel condition and investigate the tradeoff between the performance gain and the feedback overhead w.r.t. MU-MIMO CQI prediction. By exploiting MU-MIMO transmission under different spatial correlation conditions we aim at finding out the potential most efficient system configuration (feedback design and CQI update scheme) to facilitate MU-MIMO transmission for practical LTE systems.

This paper is organized as follows. The system model is introduced in Section II together with receiver structures. In Section III different MU-MIMO CQI prediction schemes in different systems are discussed in addition to impact of channel correlation on MU CQI prediction. Simulation results of the link level system performance are presented in Section IV together with discussions on the overhead of feedbacks and efficiency of the system. Section V concludes this paper.

II. System Model

Single cell downlink of the 3GPP LTE with one eNodeB and N users operating in FDD mode is considered. The eNodeB and UEs are equipped with N_{tx} and N_{rx} antenna elements, respectively. The signal received by the i-th UE, $i \in \{1, \ldots, N\}$, is given by:

$$\mathbf{y}_i = \frac{1}{\sqrt{N}}\mathbf{H}_i\mathbf{p}_i x_i + \frac{1}{\sqrt{N}}\sum_{j=1, j\neq i}^{N}\mathbf{H}_i\mathbf{p}_j x_j + \mathbf{n}_i, \qquad (1)$$

where $\mathbf{H}_i$ is the MIMO channel matrix between the eNodeB and i-th UE, $\mathbf{p}_i$ is the corresponding precoding vector from the codebook $\mathcal{C}$ with N_{C} elements, $\mathbf{p}_j$ is the precoding vector for the j-th co-scheduled UE, $\mathbf{x}_i, i \in \{1, \ldots, N\}$ is the transmitted symbol with $E\{|x_i|^2\} = 1$ and $\mathbf{n}_i$ is the zero mean circularly symmetric complex Gaussian noise vector

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with $\mathbf{n}_i \sim CN(\mathbf{0}, \sigma_n^2\mathbf{I})$. Table I summarises main downlink LTE parameters assumed in this investigation.

TABLE I
DOWNLINK LTE PARAMETERS

Parameters	Setting
Carrier frequency	2 GHz
Bandwidth	5 MHz
FFT Size	512
$N_{\mathrm{tx}} \times N_{\mathrm{rx}}$	4×2
MU-MIMO precoding	codebook precoding
UE MU receiver type	MRC and IRC
Feedback type	wideband PMI feedback
Channel models	extended SCM channel model [7]
Nr. of users	2
UE speed	3km/h

A. Receivers for MU-MIMO

In this paper, conventional low complexity MRC receiver (Transmission Mode 5, LTE Rel-8) and interference aware IRC (Transmission Mode 8, LTE Rel-9) receiver are investigated. Assuming no co-channel interference exists (MU-MIMO interference), the MRC receiver applies the matched filter $\frac{1}{\sqrt{N}}(\mathbf{H}_i\mathbf{p}_i)^{\mathrm{H}}$ on the received signal in (1) at the i-th UE in the same way as for single user MIMO. The corresponding post processing signal to noise ratio (post-SNR) is given by

$$\gamma_{\mathrm{MRC}} = \frac{\frac{1}{N}||\mathbf{H}_i\mathbf{p}_i||^4}{\frac{1}{N}\sum_{\substack{j=1,\\ j\neq i}}^{N} ||(\mathbf{H}_i\mathbf{p}_i)^{\mathrm{H}}(\mathbf{H}_i\mathbf{p}_j)||^2 + ||\mathbf{H}_i\mathbf{p}_i||^2\sigma_n^2} \quad (2)$$

The IRC belongs to a class of interference aware equalizer and in contrast to the MRC. The IRC introduces before the matched filter (MF) a whitening filter in order to suppress the interference. The general receiver structure is given by:

$$\mathbf{m}_{\mathrm{IRC}} = \frac{1}{\sqrt{N}}(\mathbf{H}_i\mathbf{p}_i)^{\mathrm{H}}\mathbf{R}_{xx,i}^{-1}, \quad (3)$$

where $\mathbf{R}_{xx,i}$ is the covariance matrix of sum of the interference and noise

$$\mathbf{R}_{xx,i} = \frac{1}{N}\sum_{j=1, j\neq i}^{N} (\mathbf{H}_i\mathbf{p}_j)(\mathbf{H}_i\mathbf{p}_j)^{\mathrm{H}} + \sigma_n^2\mathbf{I}. \quad (4)$$

By taking the correlation properties of co-channel interferers into account during the detection process, with no significant complexity increase, the IRC improves the post-SNR to be

$$\gamma_{\mathrm{IRC}} = \frac{1}{N}(\mathbf{H}_i\mathbf{p}_i)^{\mathrm{H}}\mathbf{R}_{xx,i}^{-1}(\mathbf{H}_i\mathbf{p}_i). \quad (5)$$

by suppressing the multi user interference.

III. MU-MIMO CQI PREDICTION SCHEMES

The overall performance of MU-MIMO system depends heavily on the accuracy of the SU-MIMO PMI/CQI feedback provided by the UE to eNodeB and the estimation of the proper MU-MIMO CQI at eNodeB. The inaccurate estimated MU-MIMO CQI influences link adaptation in the way of conducting eNodeB to apply a high rate modulation and coding scheme (MCS) and yielding to a high data block error rates at UE by too optimistic CQI. On the other hand, an underestimated CQI may lead to use a low rate MCS and not benefit from the instantaneous channel capacity. It is therefore of high importance that the UE provides an accurate SU-MIMO CQI and eNodeB predicts a proper MU-MIMO CQI.

A. MU-MIMO CQI prediction scheme in TM5, LTE Rel-8

In LTE Rel-8 rank one schemes, SU-MIMO PMIs and SU-MIMO CQIs are only available feedback. To keep the amount of uplink feedback limited, LTE Rel-8 is not providing any additional MU-MIMO feedback information such as information about precoders that should be used for simultaneously scheduled UEs. MU-MIMO PMIs are derived using a chordal distance approach and MU-MIMO CQIs are predicted based on SU-MIMO CQIs [1].
MU-MIMO CQI prediction in LTE Rel-8 is summarised as:
Step 1: Each UE selects precoding vector from codebook.
Step 2: Each UE reports selected PMI and corresponding rank one CQI to eNodeB via uplink control or shared channels.
Step 3: eNodeB pairs the best user pair through orthogonal precoding vector pairing (OPVP) [1] [8].
Step 4: For each UE the MU-MIMO CQI is calculated based on SU-MIMO CQI report, interfering PMI and MRC following method in [6] as

$$\mathrm{SINR}_{\mathrm{MU,MRC}} = \frac{t^2\mathrm{SINR}_{\mathrm{SU}}}{\alpha^2\mathrm{SINR}_{\mathrm{SU}} + t^2 n}, \quad (6)$$

where α is the amplitude attenuation ratio of the i-th (user 1) beam to the interference from j-th (user 2) beam and $t = \cos\frac{\Theta_{max}}{2}$, Θ_{max} is the maximum angle between neighboring beam vectors in codebook and n is the number of users spatially multiplexed. Equation (6) gives the worst case MU-MIMO CQI since the strongest interference is considered from neighboring vectors for MU-MIMO CQI prediction. The real allowed CQI can be larger by considering OPVP. Since MRC does not suppress the multi-user interference, spatial division multiple access (SDMA) method is applied such a way that users with sufficiently different Angle of Departure (AOD) are spatial-multiplexed together due to enough suppression of interference [6]. However, the residual interference makes (6) to generate relative underestimated CQIs.

B. MU-MIMO CQI prediction scheme in TM8, LTE Rel-9

In LTE Rel-9 [2], two streams of UE specific reference signals (RS) are supported for MU-MIMO transmission in the downlink dual-layer beamforming (DLBF) *transmission mode 8* (TM8). TM8 has been defined which includes both SU and MU-MIMO transmission capabilities without the need of the reconfiguration via higher layer signaling when switching between SU and MU mode on the shared data channel. With demodulation RS (DM-RS), the precoding is transparent to UE. DLBF is supported by a single transmission mode that utilises code division multiplexing (CDM) - multiplexed DM-RS transmitted on two user-specific antenna ports. The possible configurations from network side are dual-layer transmission, single-layer transmission without co-channel transmission on another layer, and single-layer transmission with co-channel transmission on another layer. Dynamic indication on which of the two UE specific antenna ports is used is supported. However, there is no explicit signalling of the presence/absence of a co-scheduled UE on the same resources, i.e. the UE does not know whether inter-layer interference exists or not. Since TM8 in LTE Rel-9 supports rank one and rank two transmission, MU-MIMO CQI prediction with adaptive rank is applied carried out in following steps:

Step 1: Each UE selects the best PMI for rank one and rank two and evaluates which rank mode increases the throughput.

Step 2: Each UE informs eNodeB about preferred PMI, RI (Rank Indicator) and the corresponding CQI. The RI reported by the UE indicates the rank with the optimum throughput. If $\mathrm{RI} = 1$, the UE reports the same SU-MIMO feedback (PMI and CQI) as in Rel-8 rank one schemes. If $\mathrm{RI} = 2$, UE reports rank two PMI and corresponding CQIs for each layer.

Step 3: For $\mathrm{RI} = 1$, the eNodeB pairs the best user pair. The method proposed in [9] have been applied in the investigation of MU-MIMO CQI prediction in LTE Rel-9. The method assumed that reported PMIs are dominant eigenvectors and based on this assumption regularized channel inversion beamforming (RI-BF) approach is applied. With the user specific DM-RS introduced in TM8, the IRC can be employed without substantial complexity increase since DM-RS allows to estimate $\mathbf{H}_i\mathbf{p}_j$ assuming that co-scheduled UE exists which is unknown to UE. The post processing SINR of IRC is approximated as:

$$\mathrm{SINR}_{\mathrm{MU,IRC}} = \frac{\mathrm{SINR}_{\mathrm{SU}}|\beta_{1,1}|^2}{1+\mathrm{SINR}_{\mathrm{SU}}|\beta_{1,2}|^2} \tag{7}$$

where, $\beta = \hat{\mathbf{H}}\hat{\mathbf{H}}^{\mathrm{H}}(\hat{\mathbf{H}}\hat{\mathbf{H}}^{\mathrm{H}} + \alpha I)^{-1}\mathrm{diag}(\mathbf{p}^{1/2})$ is a 2x2 matrix with each entry denoted as β_{ij} [9], $\hat{\mathbf{H}} = (\mathbf{p}_1, \mathbf{p}_2)$ is the constructed precoding matrix for paired UEs with PMI feedback referring to $\mathbf{p}_1$ and $\mathbf{p}_2$, $\mathbf{p} = (2\|\hat{\mathbf{H}}^{\mathrm{H}}(\hat{\mathbf{H}}\hat{\mathbf{H}}^{\mathrm{H}} + \alpha I)^{-1}\|^2)^{-1}$ is the transmit power normalization factor for the UE pair. α is a regularization factor, which can be set to 1. The SU-SINR value $\mathrm{SINR}_{\mathrm{SU}}$ is derived by the eNodeB from the reported SU-MIMO CQI.

Step 4: For $\mathrm{RI} = 2$, the eNodeB pairs two UEs with respect to maximizing system throughput. In case of IRC, the one of the rank two SU-MIMO CQIs which yields higher spectral efficiency can be directly taken as MU-MIMO CQI since multi-layer interference is already taken into account by the UEs:

$$\mathrm{SINR}_{\mathrm{MU,IRC}} = \mathrm{SINR}_{\mathrm{SU}} \tag{8}$$

C. Ideal CQI prediction

For comparison purposes, an ideal MU-MIMO CQI prediction method is considered as the upper bound for the investigated MU-MIMO throughput performance with CQI prediction. In the ideal prediction method, the post-processing SINR of IRC and MRC receivers have been calculated at eNodeB following (2) and (5), respectively. It is assumed that perfect knowledge on the downlink channel $\mathbf{H}_i$ and the noise power σ_n^2 at each UE are available at eNodeB.

D. CQI prediction and channel spatial correlation

In addition to the accuracy of feedback information on PMI/CQI, performances of the different CQI prediction schemes in different transmission modes also depend on the channel propagation scenario, namely the spatial correlation of the MIMO channels. In order to illustrate such effects, it is assumed that $\mathbf{H}_i$ in (1) represents a realisation of spatial MIMO channels and applying eigendecomposition (ED) on it yields

$$\mathbf{H}_i^{\mathrm{H}}\mathbf{H}_i = \mathbf{V}\mathbf{\Lambda}\mathbf{V}^{\mathrm{H}}, \tag{9}$$

with

$$\mathbf{V} = [\mathbf{v}_1, \mathbf{v}_2, \cdots, \mathbf{v}_{N_{\mathrm{tx}}}] \tag{10}$$

and

$$\begin{aligned}\mathbf{\Lambda} = \mathrm{diag}\left(\lambda_1, \lambda_2, \cdots, \lambda_{N_{\mathrm{tx}}}\right), \\ \lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_{N_{\mathrm{tx}}},\end{aligned} \tag{11}$$

being the matrix of eigen vectors and diagonal matrix of associated eigen values, respectively. As given in Section III-A SDMA with widely separated AOD is applied to UEs, which indicates a high spatial correlation to a single UE and uncorrelated channels between UEs. In this scenario, a dominant beam is viewed by UE associated with large power, which means the optimal precoding for the i-th UE is $\mathbf{v}_1$ with channel gain of $\lambda_1, \lambda_1 \gg \lambda_k, k = 2, \cdots, N_{\mathrm{tx}}$. A visualized representation of this scenario is depicted in Figure 1, where a single dominative beam can be clearly seen. Other sidelobs mismatch to the direction of main beam and therefore yield negligible interference. More freedom is given for UE pairing in this scenario. In addition, MU-MIMO CQI can be more accurate predicted from SU-MIMO CQI due to small residual mutual interference. In the case of low or medium spatial correlations, which means e.g. $\lambda_1 \approx \lambda_2$, two dominant beams exist pointing to a single UE as depicted in Figure 2. Similarly, UE pairing shall be carried out only in the sidelobs with small amplitudes in this scenario. However, due to more potential interference beams, less directions are available and consequently less freedom for UE pairing. In such low/medium spatially correlated channels, rank one based SU-MIMO PMI and CQI feedback in Rel-8 TM5 may not help to find out the

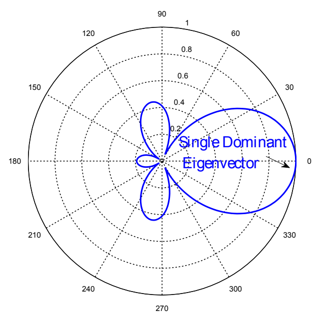

Fig. 1. Downlink beams in spatially high correlated channel

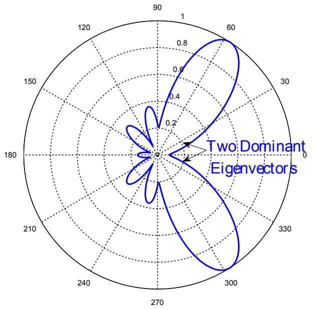

Fig. 2. Downlink beams in spatially medium correlated channel

potential optimal UE pairing and yields a small and inaccurate MU-MIMO CQI in (6) even through OPVP is used.

In the case of MU-MIMO CQI prediction in Rel-9 TM8, more feedback information is provided by UE to eNodeB since RI is reported together with SU-MIMO PMI and CQI, as discussed in Section III-B. The UE is aware of the instantaneous channel condition in terms of rank value and reports it as well. Even through the freedom of UE pairing is limited by the property of the spatially low/medium correlated channel, the reported rank two PMIs and layer-specific CQIs guarantee a correct UE pairing, less mutual interference, and furthermore a proper MU-MIMO CQI prediction for scheduling and transmission. From this point of view, the system throughput and QoS will be improved. For better explanation, Figure 3 demonstrates the probability distribution functions (PDF) of $r_\lambda = \frac{\lambda_1}{\lambda_2}$ in high (0.9) and medium correlation (0.3) scenarios. It can be seen that r_λ distributed more widely in spatially high correlated channel indicating large ratio between self channel power and interference channel power. On the other hand, UE-specific transmission will be strongly disturbed with smaller r_λ in uncorrelated case due to the larger interference power.

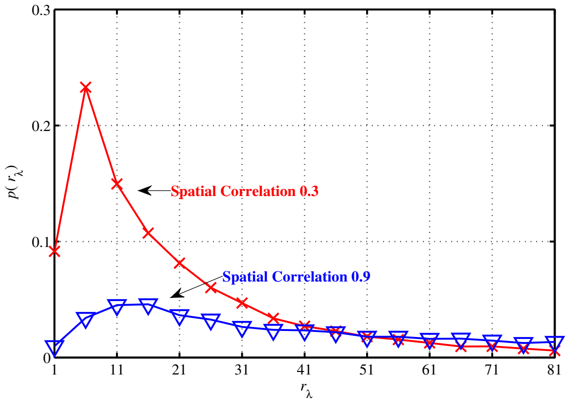

Fig. 3. Probability density function of r_λ

IV. Simulation Results and Discussions

The results of investigation are shown in Figures 4 and 5 for low and high spatial correlation, respectively. Mean throughput performances are depicted as a function of the SNR per receive antenna in dB. Considering that MU-MIMO is more suitable in low-mobility scenarios where the feedback can be better exploited, mobile speed of 3 km/h is investigated. Ideal channel estimation, HARQ, Adaptive Modulation and Coding (AMC) and no feedback delay have been assumed. The extended spatial channel model (SCME) [7] and uniform linear array (ULA) antenna array with 0.5λ or 4λ spacing as two examples representing high/low correlated antenna configurations have been applied.

In Figure 4, comparison between two different feedback modes and ideal MU-MIMO CQI prediction methods is shown. Clearly, MU- MIMO CQI (MU-CQI) prediction based

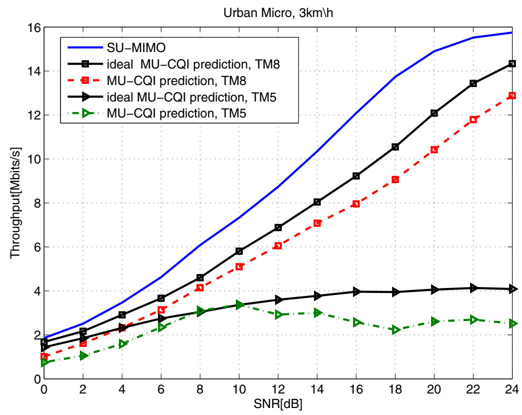

Fig. 4. Performance evaluation in spatially low correlated channel

on adaptive rank outperforms rank one MU-MIMO CQI prediction significantly when SNR increases. Due to the lack of the interference suppression function, MRC receiver faces stronger distortion from residual mutual interference in MU-MIMO transmission and therefore has smaller post SINR. This fact results to low data rate (modulation and coding scheme (MSC) with low spectral efficiency) being scheduled to MRC UE by eNodeB in order to keep certain QoS level, e.g. 10% block error ratio (BLER). Since IRC receiver is able to reject the mutual interference, higher MCS is assigned to IRC UE with larger SNR and yields higher throughputs. However, adaptive rank MU-MIMO CQI prediction in TM8 requires more feedback as explained in the next subsection and shown in Table II, but less precoding operations at eNodeB and easier channel estimations at UE. Comparing to the ideal CQI predication case, realistic rank two MU-MIMO CQI prediction yield degradation of 2 dB. Such degradation is caused by practical system implementation and is acceptable.

Similar results can be observed in Figure 5. Due to the high correlation channel and orthogonal UE pairing or RI-BF, the residual mutual interference here is significantly less than in Figure 4. Furthermore, according to Section III-D more freedoms of UE pairing exist in Figure 5 than in Figure 4. Therefore the rank one MU-MIMO CQI prediction works better under high correlation scenario with large MCS being scheduled. In addition, performance of rank two MU-MIMO CQI prediction methods comes closer to SU-MIMO compared

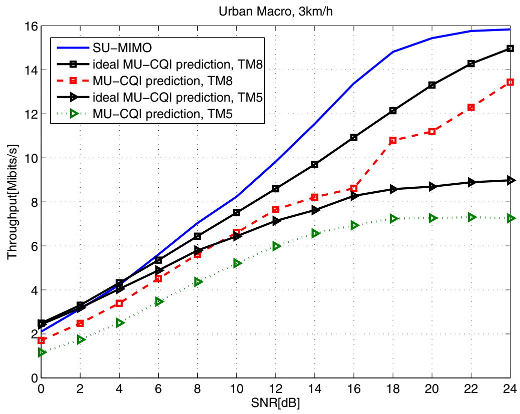

Fig. 5. Performance evaluation in spatially high correlated channel

with the results in Figure 4 due to the same reason of less residual mutual interference.

A. Feedback overhead

The feedback overhead follows the design of LTE systems with Rel-8 and Rel-9. As presented in Table I, we assume wideband PMI feedback, wideband RI and wideband CQI feedback as the MU-MIMO transmission configurations. Table II summarises the feedback overhead of different feedback configuration with considering of the parameters in Table I. In Table II, Q_{PMI} is the N_{tx} dependent number

TABLE II
FEEDBACK OVERHEAD FOR DIFFERENT CQI PREDICTIONS

Feedback Configuration	**Feedback Overhead**
Rank 1, TM5	$Q_{\mathrm{PMI}} + Q_{\mathrm{CQI}}$
Adaptive Rank, TM8	$Q_{\mathrm{PMI}} + Q_{\mathrm{CQI}} \times (p_{\mathrm{RI}=1} + 2\,p_{\mathrm{RI}=2})$

of bits for the wideband PMI, Q_{CQI} is the number of bits for the CQI feedback, and $p_{\mathrm{RI}=1}, p_{\mathrm{RI}=2}$ are the probabilities of selecting single rank and dual rank transmissions at UE, respectively. With the system configurations in Table I, and $Q_{\mathrm{PMI}} = 4, Q_{\mathrm{CQI}} = 4$ we can estimate the maximum feedback overhead for MU-MIMO CQI prediction schemes as summarised in Table III. From Table III it can be seen that up to 50% additional feedback are required for "Adaptive Rank TM8" based CQI prediction scheme, however leading to more than tripled throughput in low correlation scenario and 20% improvement in high correlation scenario in contrast to "Rank 1 TM5". The near constant throughput given by "Adaptive Rank TM8" indicates that MU-MIMO CQI prediction with IRC is more robust within TM8 Rel-9 LTE systems.

V. CONCLUSIONS

In this paper different, MU-MIMO CQI prediction methods based on rank one and rank two transmission have been investigated and evaluated considering the downlink 3GPP LTE system with MU-MIMO support. Effect of channel conditions on the accuracy of MU-MIMO CQI reporting is analysed and illustrated. The results have shown that the CQI prediction accuracy deteriorates in low spatially correlated channels due to less freedom for UE pairing. However, this limitation can be compensated through the rank adaption since more feedback information is provided by the UE. Furthermore, the results have shown that MU-MIMO CQI prediction based on adaptive rank shows near a constant throughput and outperforms rank one MU-MIMO CQI prediction significantly when SNR increases. Even adaptive rank CQI prediction requires more feedback, less precoding operations and easier channel estimations at UE is required and as such is more robust and practicable for LTE systems beyond Rel-8.

TABLE III
MU-MIMO SYSTEM EFFICIENCY COMPARISION @ SNR = 16 dB

MU-MIMO / Receiver	**Max Feedback Overhead**	**Channel Correlation**	**UE Throughput**
Adapt. Rank, TM8 / IRC	12 bits	low	8.0 Mbits/s
Rank 1, TM5 / MRC	8 bits	low	2.5 Mbits/s
Adapt. Rank, TM8 / IRC	12 bits	high	8.5 Mbits/s
Rank 1, TM5 / MRC	8 bits	high	7.0 Mbits/s

VI. ACKNOWLEDGMENT

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