

Fair Performance Comparison between CQI- and CSI-based MU-MIMO for the LTE Downlink

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Abstract—We compare the performance of the downlink of a 3GPP UTRAN Long Term Evolution (LTE) system with multi-user (MU) multiple input multiple output (MIMO) support and channel state information (CSI) feedback to a standard MU-MIMO LTE system utilizing channel quality indicator (CQI) feedback only. For the latter case, we propose an efficient method for estimating the appropriate MU-MIMO transmission parameters based on the LTE Release 8 feedback, which is not providing any additional MU-MIMO feedback information. In order to facilitate a fair performance comparison, we spend approximately the same number of feedback bits for both feedback methods and we evaluate which method performs better in the considered scenario for various cases by means of extensive system-level simulations, assuming a low-rate feedback channel. It is shown that significant performance gains may be realized with both proposed feedback methods compared to conventional LTE Release 8 networks without MU-MIMO support.

I. INTRODUCTION

Multiple antenna transmission and reception is one of the key concepts for the next generation of cellular systems, such as the 3GPP Long Term Evolution (LTE), to provide high data rates to a large number of different users. LTE Release 8 actually supports both single-user multiple-input multiple-output (SU-MIMO) schemes including spatial multiplexing and closed-loop transmit diversity as well as a multi-user (MU) MIMO mode, in which multiple user equipments (UEs) can be served simultaneously on the same frequency resources [1]. Lately, various MU-MIMO techniques have been intensively investigated in literature due to numerous advantages over conventional SU-MIMO schemes, such as the spatial decorrelation of the channel due to spatially separated antennas or the fact that spatial multiplexing gain can be achieved even without multiple antennas at the UE side [2]. However, the performance of MU-MIMO generally is heavily dependent on the availability of accurate channel state information (CSI) at the base station (BS) side, where the interference suppression between simultaneously served UEs is carried out [3]. As a consequence, appropriate feedback methods are a crucial factor for making MU-MIMO schemes practical for cellular systems, in particular for frequency-division duplexing (FDD) systems. In contrast to time-division duplexing systems, where CSI can be easily obtained by exploiting the channel reciprocity of the uplink and downlink, obtaining downlink CSI in FDD systems is more involved since the uplink and downlink channels are usually approximately uncorrelated due to their separation in frequency. For this reason, several different

feedback concepts have been developed in recent years to ease the FDD uplink feedback requirements [4], [5].

A resource-efficient feedback solution, which has also found its way into the current LTE Release 8 specifications, is based on a channel quality indicator (CQI), which is reported along with a precoding matrix indicator (PMI) back to the BS. In this regard, the UE selects the most suitable precoder under the current channel conditions from a finite precoder codebook and determines the corresponding PMI as well as the CQI, which is an indication of the supportable data rate. Another promising feedback method is based upon vector quantization techniques, where the estimated CSI is efficiently quantized at the UE side and then fed back to the serving BS via a low-rate feedback channel [6], [7]. Thus, suitable precoders can be designed directly at the BS side leading to a higher flexibility compared to the CQI-based approach. However, this feedback method represents a major shift in the feedback paradigm compared to LTE Release 8, but with view to future LTE-Advanced transmission techniques [8], more sophisticated CSI-based feedback methods are currently under discussion for realizing these techniques in practice.

In this paper, we investigate and evaluate two fundamentally different low-rate feedback methods based on CQI and CSI, respectively, considering the downlink of 3GPP LTE cellular networks with MU-MIMO support, which contains SU-MIMO transmission as special case. In this regard, we propose for the CQI-based approach an efficient method for acquiring the appropriate MU-MIMO transmission parameters based on conventional LTE Release 8 feedback, which is not providing any special MU-MIMO feedback information. Furthermore, we thoroughly analyze the achievable performance of the proposed CQI-based MU-MIMO scheme and compare it to our CSI-based MU-MIMO scheme proposed in [9]. For that purpose, we spend the same amount of feedback bits for both feedback methods leading to a fair performance comparison that provides a basis for evaluating which feedback method performs better for the considered scenario.

This paper is organized as follows: In Section II and III, we describe the proposed CQI- and CSI-based MU-MIMO schemes in detail. Afterwards, we outline our simulation methodology in Section IV, followed by some system-level simulation results in Section V. Finally, our conclusions are given in Section VI.

II. CQI-BASED MU-MIMO SCHEME

We consider the downlink of a 3GPP LTE Release 8 system operating in FDD mode, where all BS sectors and UEs are equipped with M and N different antenna elements, respectively. In LTE Release 8, the UEs periodically send dedicated CQI reports back to their serving BS, containing CQI values, a PMI as well as a rank indicator (RI). A CQI value corresponds to the spectrally most efficient modulation and coding scheme (MCS) that can be supported by the current downlink channel without exceeding a given target block error rate. In general, the number of reported CQI values is depending on the RI, which specifies the number of spatial layers that can be supported. According to the standard CQI reporting in LTE Release 8, the total available bandwidth is subdivided into L different subbands and for each of these subbands a separate CQI report is generated in order to exploit the frequency selectivity of the channel. However, UEs may only report one wideband RI for the whole bandwidth due to signaling constraints. Thus, even if a certain UE is scheduled on multiple physical resource blocks (PRBs), always the same number of streams have to be transmitted. In this regard, we assume that the UEs can request either beamforming or spatial multiplexing as transmission scheme and we determine the wideband RI based on the ratio of the maximal achievable rates over the whole bandwidth as follows

$$\text{RI} = \begin{cases} 1, & \text{if } \lambda \geq \lambda_{\text{thr}} \\ > 1, & \text{if } \lambda < \lambda_{\text{thr}} \end{cases}, \quad (1)$$

where λ is defined as

$$\lambda = \frac{\sum_{l=1}^L \max_{x \in X} (R_{\text{beam}}(l, x))}{\sum_{l=1}^L \max_{y \in Y} (R_{\text{smux}}(l, y))}, \quad (2)$$

with λ_{thr} as a predefined threshold value for comparing the achievable rates R of both transmission schemes, and X as well as Y as the standardized set of LTE Release 8 precoders used for beamforming and spatial multiplexing, respectively [1]. In order to keep the amount of uplink feedback limited, the current LTE Release 8 standard is not providing any additional MU-MIMO feedback information such as information about precoders that should be used for simultaneously scheduled UEs, for example. For that reason, we briefly outline in the following a method to obtain appropriate MU-MIMO transmission parameters based on the LTE Release 8 SU-MIMO feedback in order to enable channel-aware scheduling and link adaptation for MU-MIMO transmission.

First of all, every BS can identify potential candidates for MU-MIMO transmission based on the RIs reported by the various UEs since UEs which have been selected by the scheduler for MU-MIMO transmission are only allowed to transmit a single data stream due to signaling constraints in the downlink. Consequently, the signal received on a single subcarrier by the k -th UE in case of MU-MIMO transmission

can be expressed as

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{w}_k s_k + \mathbf{H}_k \sum_{\substack{j=1 \\ j \neq k}}^K \mathbf{w}_j s_j + \mathbf{i}_k + \mathbf{n}_k, \quad (3)$$

where K denotes the number multiplexed UEs, \mathbf{H}_k denotes the $N \times M$ -dimensional MIMO channel of UE k , \mathbf{w}_k denotes one of the standardized beamforming precoding vectors for LTE Release 8 of dimension $M \times 1$, s_k denotes the symbol transmitted by the UE k , and \mathbf{i}_k as well as \mathbf{n}_k cover the inter-cell interference and thermal noise, respectively. Furthermore, we assume that

$$\mathbb{E} \left[\left\| \sum_{j=1}^K \mathbf{w}_j s_j \right\|^2 \right] \leq P_T, \quad (4)$$

i.e., the total transmit power per subcarrier is always constrained to P_T . In order to minimize the intra-cell interference caused by simultaneously served UEs, we restrict multiplexed UEs to be scheduled on orthogonal beams only, so that the precoders in (3) are subject to the following restriction

$$\langle \mathbf{w}_i, \mathbf{w}_j \rangle = 0, \quad i, j = 1, \dots, K, \quad i \neq j, \quad (5)$$

where $\langle \cdot \rangle$ denotes the inner product. This way, also additional downlink signaling of the precoding information can be omitted as well¹. After dividing the UEs suited for MU-MIMO transmission into groups with orthogonal precoders, every BS finally estimates the achievable MU-MIMO rates of all possible UE combinations based on the reported SU-MIMO CQI values in order to perform frequency-selective proportional fair (PF) scheduling similar to the algorithm proposed in [10]. In this regard, the scheduler generally aims at maximizing the weighted sum rate for each PRB as given by the sum of the PF metrics of the various UEs to be scheduled on the same frequency resources.

For estimating the achievable MU-MIMO rates, we determine the corresponding MU-MIMO signal-to-interference-plus-noise ratio (SINR) values by estimating the SINR loss compared to the SU-MIMO case, which is caused by the additional intra-cell interference as well as by the fact that the transmit power is split among simultaneously scheduled UEs, where we assume an equal split-up. This is also confirmed by Fig. 1, where we compare the SU-MIMO with the MU-MIMO SINR distribution. It can be seen from Fig. 1 that the impact of the intra-cell interference is SINR dependent. This is because, in general, the intra-cell interference is almost negligible compared to noise and inter-cell interference for low SU-MIMO SINR values whereas it is getting more significant for high SINR values. As a result, we have empirically determined a look-up table for the MU-MIMO SINR loss, which is also illustrated in Fig. 1, considering the system-level

¹Please note that the receiver performance may be improved by taking the occurring intra-cell interference into account. This, however, requires knowledge about the used precoders of simultaneously served UEs. Clearly, by using orthogonal precoders as outlined in (5) this knowledge is already available at the UE side without any further downlink signaling.

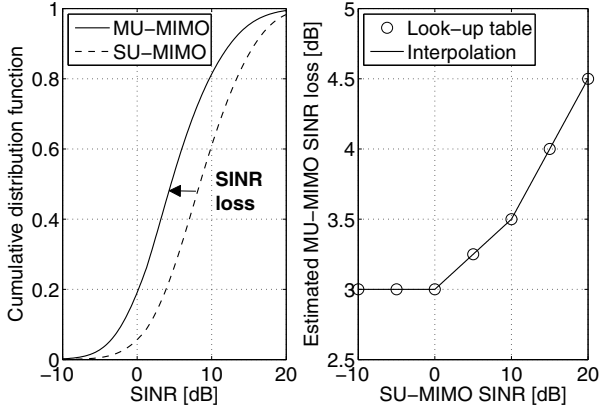


Fig. 1. Distribution of the SINR values for SU-MIMO as well as for MU-MIMO transmission only and the empirically determined MU-MIMO SINR loss as a function of SU-MIMO SINR values.

parameters given in Table I. Based on the estimated SINR values, the corresponding MU-MIMO rate for one user can then be calculated by means of the Shannon capacity formula as follows

$$R = \log_2(1 + \text{SINR}), \quad (6)$$

thus enabling frequency-selective PF scheduling and link adaptation without any dedicated MU-MIMO feedback. Please note that the computational complexity with respect to UE grouping and achievable rate estimation is significantly depending on the number of active UEs per BS. However, the additional computing time should be rather low since on the one hand often only a few UEs per BS are active in practice, and on the other hand more powerful hardware is generally used at the BS side for facilitating fast processing.

III. CSI-BASED MU-MIMO SCHEME

In the following, we briefly review our CSI based MU-MIMO scheme for the downlink of LTE cellular networks that is explained in more detail in [9]. The feedback method for this approach represents a major shift in the feedback paradigm compared to LTE Release 8 since each UE reports a quantized version of its estimated downlink channel back to its serving BS². In this regard, only one quantized channel matrix is fed back for each subband in order to keep the uplink feedback load limited. Hence, as outlined in [9], the set of all channel estimates for subband s ($s = 1, \dots, L$) are arithmetically averaged as

$$\bar{\mathbf{H}}_s = \frac{1}{K_s} \sum_{k=1}^{K_s} \tilde{\mathbf{H}}_{k,s}, \quad s = 1, \dots, L, \quad (7)$$

²Please note that with a CSI-based precoding scheme at the BS side as considered here, the UEs generally have to estimate also the used precoders for being able to demodulate the transmitted signals. In this regard, we assume that additional UE-specific reference symbols are introduced during data transmissions, which are precoded with the same precoding weights as the actual data symbols.

where $\tilde{\mathbf{H}}_{k,s}$ and K_s denote the k -th estimated downlink channel within subband s and the number of estimated channels per subband, respectively. In order to allow for a flexible allocation of feedback bits, the direction and magnitude information of

$$\mathbf{h}_s = \text{vec} \bar{\mathbf{H}}_s = [\mathbf{h}_1^T \quad \mathbf{h}_2^T \quad \dots \quad \mathbf{h}_M^T]^T \quad (8)$$

are separately quantized, where the quantized channel direction is calculated as

$$\hat{\mathbf{h}}_{\text{direc}} = \arg \min_{\mathbf{c}_m \in C} d_c \left(\frac{\mathbf{h}_s}{\|\mathbf{h}_s\|}, \mathbf{c}_m \right), \quad m = 1, \dots, 2^{B_{\text{direc}}}, \quad (9)$$

with B_{direc} and $C = \{\mathbf{c}_m\}_{m=1}^{M_{\text{direc}}}$ as the number of feedback bits for reporting the channel direction information and the codebook consisting of $M_{\text{direc}} = 2^{B_{\text{direc}}}$ unit norm vectors, respectively. Moreover, the channel direction codebook C is constructed based on the well-known Linde-Buzo-Gray algorithm proposed in [11]. According to (9), we quantize the direction information $\mathbf{h}_s/\|\mathbf{h}_s\|$ by finding the codebook vector which minimizes the chordal distance

$$d_c(\mathbf{r}_i, \mathbf{r}_j) = \sqrt{\frac{1}{2} \left(1 - (\mathbf{r}_i^H \cdot \mathbf{r}_j)^2 \right)}, \quad (10)$$

where \mathbf{r}_i and \mathbf{r}_j are both unit norm vectors. Finally, the channel magnitude information is quantized by applying a simple scalar quantizer using equidistant quantization intervals within the region

$$\min_{1 \leq m \leq M_{\text{direc}}} \|\mathbf{c}_m\| \leq \|\mathbf{h}_s\| \leq \max_{1 \leq m \leq M_{\text{direc}}} \|\mathbf{c}_m\|. \quad (11)$$

Apart from the downlink channel information, additional information about the experienced interference situation of the UEs is required at the BS side to design appropriate precoders as well as to efficiently perform link adaptation. For that purpose, we feed back the long term-interference level observed by a certain UE only, because on the one hand the uplink signaling can be significantly reduced in this way and on the other hand the interference situation is instantaneously changing from one transmission time interval (TTI) to the next anyway since different UEs with different precoders might be scheduled. Furthermore, we consider regularized block diagonalization (RBD) as proposed in [12] for designing the precoders in case of MU-MIMO, which allows arbitrary antenna configurations and number of multiplexed UEs. The fundamental idea of RBD is to separate the intra-cell interference suppression from the system performance optimization, thus the precoding vector \mathbf{w}_k in (3) is factorized as follows [12]

$$\mathbf{w}_k = \mathbf{W}_{k,a} \cdot \mathbf{w}_{k,b}. \quad (12)$$

In a first step the $M \times M$ -dimensional matrix $\mathbf{W}_{k,a}$ is used to suppress the intra-cell interference between the simultaneously served UEs on the same frequency resources and then in a second step the system performance is further improved by designing $\mathbf{w}_{k,b}$ in such a way that the SINRs of the various UEs are maximized. Let us define

$$\tilde{\mathbf{H}}_k = \left[\hat{\mathbf{H}}_1^T \cdots \hat{\mathbf{H}}_{k-1}^T \quad \hat{\mathbf{H}}_{k+1}^T \cdots \hat{\mathbf{H}}_K^T \right]^T = \tilde{\mathbf{U}}_k \tilde{\mathbf{\Lambda}}_k \tilde{\mathbf{V}}_k^H, \quad (13)$$

where $\hat{\mathbf{H}}_k$ denotes the quantized channel matrix fed back from k -th UE for the subband the considered PRB belongs to. Then, the matrix $\mathbf{W}_{k,a}$ generally can be expressed as

$$\mathbf{W}_{k,a} = \tilde{\mathbf{V}}_k \left(\tilde{\mathbf{\Lambda}}_k^T \tilde{\mathbf{\Lambda}}_k + \frac{KN\sigma_n^2}{P_T} \mathbf{I}_M + \frac{\bar{P}_{I,k}}{P_T} \mathbf{I}_M \right)^{-1/2}, \quad (14)$$

where we consider in contrast to the original RBD approach proposed in [12] additionally the prevalent inter-cell interference. Moreover, σ_n^2 in (14) denotes the mean thermal noise power per subcarrier and $\bar{P}_{I,k}$ covers the mean inter-cell interference power received by the k -th UE, which can be estimated by the serving BS based on the reported interference information from UE k . After having suppressed the intra-cell interference, the precoding vector $\mathbf{w}_{k,b}$ aims at maximizing the SINR of the UE k under the assumption that the MU-MIMO channel is decomposed into a set of parallel independent SU-MIMO channels. Hence, $\mathbf{w}_{k,b}$ is chosen as the eigenvector corresponding to the strongest eigenvalue of the k -th UE's effective channel

$$\hat{\mathbf{H}}_{\text{eff}} = \hat{\mathbf{H}}_k \mathbf{W}_{k,a}. \quad (15)$$

Finally, we would like to point out that in case of SU-MIMO transmission the intra-cell interference is non-existent and therefore the matrix $\mathbf{W}_{k,a}$ in (14) becomes the identity matrix.

IV. SIMULATION METHODOLOGY

We compare the system performance of both proposed MU-MIMO schemes by means of extensive system-level simulations for a standard hexagonal grid consisting of 19 sites with three sectors per site. Furthermore, we apply the wrap around technique in order to avoid any border effects and multi-path fading is modeled by means of the 3GPP spatial channel model (SCM). The reference signaling overhead is simulated for both MU-MIMO schemes according to [1], where apart from the cell-specific reference symbols additional UE-specific reference symbols are taken into account for the CSI-based scheme since UEs generally have to estimate also the used precoders for being able to demodulate the transmitted signals. Besides, if not stated otherwise we assume that there are always 10 UEs uniformly distributed in each sector. Further system parameters are given in Table I.

In order to evaluate which feedback method performs better in the considered LTE scenario, a fair performance comparison will be considered in the following. To this end, we approximately spend the same amount of feedback bits per subband for both MU-MIMO schemes, which is also outlined in Table II for the case that all BS sectors and UEs are equipped with two antenna elements. While the MCS as well as the PMI are signaled for each CQI report, the RI is only reported for the whole bandwidth. Thus, we are neglecting the required number of feedback bits for signaling the RI in our further considerations. As a result, we spend approximately 8 bits per subband on average, under the reasonable assumption that in 20% of all cases spatial multiplexing is requested as transmission scheme by the UEs. The same holds for the CSI-based method, if we also neglect the required feedback bits

TABLE I
SYSTEM LEVEL SIMULATION PARAMETERS

Parameter	Setting
Deployment scenario	19 sites with 3 sectors per site
Inter-site distance (ISD)	500 m [Macro 1] or 1732 m [Macro 3]
Carrier freq. / bandwidth	2.0 GHz / 10 MHz
Channel model	3GPP SCM
Distance-dependent path loss	According to 3GPP TR 25.814 [13]
Shadowing standard deviation	8 dB
UE speed	3 kmph (quasi-static)
Default number of UEs/sector	10
UE / BS antennas	2 / 2 per sector
UE receiver types	MRC (single stream) / Linear MMSE (dual stream)
UE category	5 (incl. 64-QAM support)
Scheduling algorithm	Proportional-fair according to [10]
BS / UE antenna spacing	$10 \lambda / \frac{\lambda}{2}$, λ : wavelength
BLER target	Optimized with respect to average spectral efficiency for each setting
Default reporting subband size	5 PRBs
Report generation interval	5 TTIs
Feedback delay	7 TTIs
HARQ model	Synchronous, non-adaptive
Parallel HARQ processes	8
Traffic model	Full buffer services
Pilot overhead	Simulated according to [1]
Control channel overhead	First 3 OFDM symbols per subframe
Link to system interface	MIESM [14]
Predefined threshold λ_{thr}	0.45

TABLE II
UPLINK FEEDBACK LOAD.

CQI feedback	Bits per subband
MCS for single/dual stream transmission	5/10
Precoding matrix indicator	2
CSI feedback	Bits per subband
Channel direction information	5
Channel magnitude information	3

for signaling the long-term interference level which in fact is reasonable since the reporting interval in that case may be much longer than for the CSI feedback.

V. SIMULATION RESULTS

Figure 2 shows the system performance comparison between CQI-based and CSI-based SU-MIMO as well as MU-MIMO for the Macro 1 case, where the LTE Release 8 system with SU-MIMO support only and CQI feedback is used as a reference. Both the average spectral efficiency as well as the cell-edge throughput defined as the 5th percentile of the UE throughput distribution are illustrated. It can be seen from Figure 2 that even with a low-rate feedback channel significant gains can be achieved with MU-MIMO support in the order of 10% for the average spectral efficiency as well as cell-edge throughput. Please note that the illustrated performance gains due to MU-MIMO support can be achieved without the need to increase the uplink feedback load compared to the CQI-based SU-MIMO reference. Furthermore, we note that the performance gains for the CQI-based method are slightly higher than for the CSI-based method. This can be explained

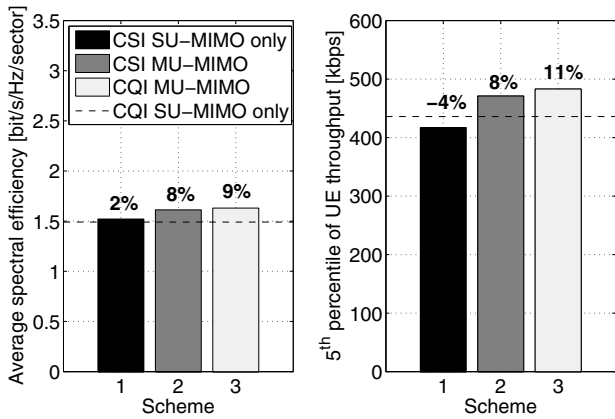


Fig. 2. System performance comparison between CQI- and CSI-based SU-MIMO as well as MU-MIMO for the Macro 1 case. The given percentages denote the relative performance gains compared to a conventional CQI-based SU-MIMO system.

by the fact that the reported interference information by the UEs is less reliable in case of CSI feedback since precoders are individually designed at the BS and are changing from one TTI to the next. Thus, the link adaptation process and in particular the MCS selection becomes more inaccurate, what hence leads to a significant performance degradation.

Figure 3 shows the impact of the number of active UEs per BS sector on the system performance for the Macro 1 and Macro 3 case, respectively. Clearly, the average spectral efficiency can be improved with increasing number of active UEs due to the higher MU diversity in that case. Thus, the scheduler can better exploit the spatial separability among the active UEs in order to mitigate interference caused by simultaneously served UEs. By contrast, the cell-edge throughput decreases with increasing number of active UEs, because less PRBs can be assigned to cell-edge UEs by the frequency-selective PF scheduler. Similar to the results in Figure 2, it can be also seen from Figure 3 that the CQI-based method performs slightly better than the CSI-based one.

Figure 4 illustrates the impact of the reporting subband size ranging from one—corresponding to the situation where for each PRB a feedback report is generated—to 50 where a single wideband report is fed back for the whole bandwidth. As can be seen, with smaller reporting granularity the system performance becomes steadily better. This is because the feedback reflects much better the current channel and interference variations with a finer resolution in the frequency domain, thus leading to an improved frequency-domain scheduling. However, this comes at the cost of an increased uplink overhead.

Finally, Figure 5 depicts the probabilities that a certain transmission scheme is selected for the CQI-based as well as for the CSI-based method with and without MU-MIMO support. It can be seen that the probability for selecting one of the SU-MIMO transmission schemes and in particular for selecting spatial multiplexing is significantly reduced in case

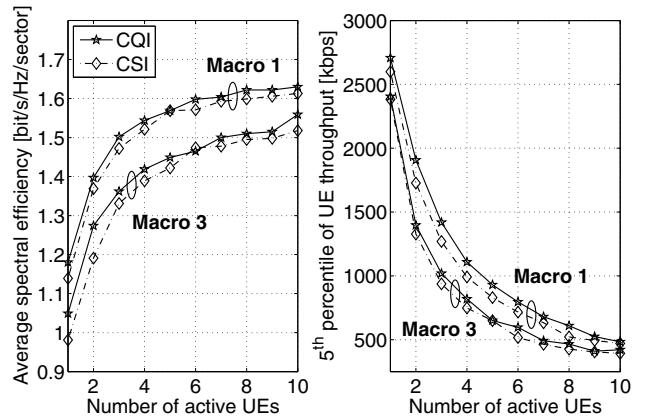


Fig. 3. Impact of the number of active UEs per BS sector on the system performance for the Macro 1 and Macro 3 case.

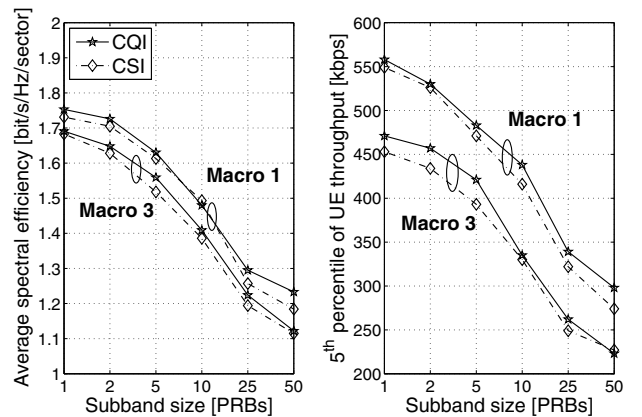


Fig. 4. Impact of the reporting subband size on the system performance for the Macro 1 and Macro 3 case.

of MU-MIMO support for both CQI and CSI feedback. This is because the scheduler makes use of the MU diversity by selecting spatially separated UEs for simultaneous transmission on the same frequency resources, thus reducing the spatial correlation of the channel compared to the SU-MIMO case due to transmitting two data streams to spatially separated UE antennas. As a result, in most of the cases a higher throughput gain can be achieved with MU-MIMO transmission, even if the transmit power has to be shared between co-served UEs.

VI. CONCLUSION

We have evaluated the achievable performance of two different MU-MIMO schemes for the downlink of 3GPP LTE cellular networks based on CQI and CSI feedback, respectively. While the CQI feedback concept is in line with the LTE Release 8 feedback, the proposed CSI concept, in contrast, represents a major shift in the feedback paradigm compared to LTE Release 8 since quantized channel and interference information is fed back to the BS side. In order to achieve a fair performance comparison between both feedback methods, we have spent approximately the same amount of

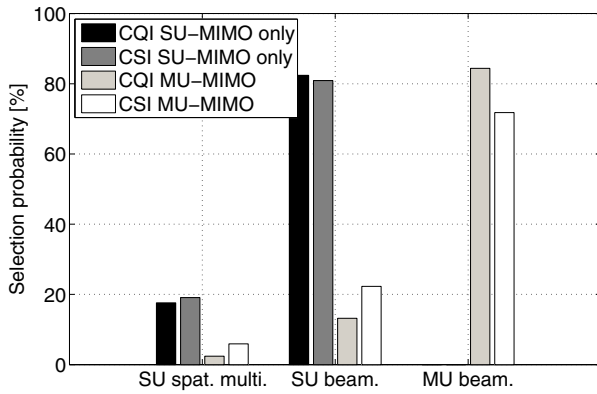


Fig. 5. Transmission scheme selection probabilities of various cases for the Macro 1 case.

feedback bits per subband and it turned out that the CQI-based method performs slightly better for the considered scenarios. In this regard, the individual design of the precoders at the BS constitutes a main drawback of the CSI-based method since the interference situation can be predicted less reliably. This problem may be partially mitigated by predicting the interference situation during the actual data transmission already in advance. The interference prediction in turn can be accomplished through a BS cooperation similar to the approach presented in [15] for the 3GPP LTE uplink, what will be part of our future work.

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