Explicit vs. Implicit Feedback for SU and MU-MIMO.

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Explicit vs. Implicit Feedback for SU and MU-MIMO

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Abstract—SU and MU-MIMO performance relies on accurate link adaptation in order to benefit from multi-user scheduling, beamforming, adaptive coding and modulation. Such accuracy highly depends on the type of the channel state information feedback. LTE-Advanced has defined two major types of feedback, i.e. implicit and explicit feedback. Implicit feedback makes some assumptions on the transmit precoding and receiver processing at the time of CSI and CQI feedback. The CSI is expressed in terms of a recommended precoder, commonly denoted as PMI. Explicit feedback refers to the feedback of channel information without making any assumption on the transmit and receiver processing. In this paper, we discuss pros and cons of such feedback mechanisms for both SU and MU-MIMO and compare performance of both approaches using system level simulations compliant with LTE-A system. It is shown that implicit feedback is the preferred feedback framework for both SU and MU-MIMO.

I. INTRODUCTION

LTE-Advanced has recently introduced user specific reference signals, also denoted as demodulation reference signals (DM-RS), to further improve performance of MIMO, especially Multi-user (MU) MIMO. It enables the use of more advanced transmit filtering at the Base Station (BS) and more advanced feedback mechanisms at the user equipment (UE). LTE-Advanced has identified two categories of feedback mechanisms [1], i.e. implicit and explicit feedback.

Explicit feedback of the channel state/statistical information consists in feeding back the channel as it is observed by the receiver without assuming any hypothetical transmission scheme or any receiver processing. Explicit feedback information may include the short term channel matrix $H$, the instantaneous channel covariance matrix $H^H H$ or its average in time or frequency. For both the channel matrix and the covariance matrix, the full information or just its dominant eigen components may be reported.

Implicit feedback of the channel state/statistical information is the feedback mechanism used in LTE Rel. 8. It consists in making some hypotheses on the transmission and/or reception processing at the time of feedback. Typical contents of such feedback mechanism are the well known Channel Quality Indicator (CQI), Precoding Matrix Indicator (PMI) and Rank Indicator (RI). The UE could e.g. assume at the time of feedback that it will be scheduled in single-user (SU) and that the receiver processing is based on MMSE.

The literature has also investigated to some extent the difference between implicit and explicit feedback for MU-MIMO even though such terminology is not used in the academic literature. As an example, schemes performing Zero-Forcing Beamforming (ZFBF) [2] and relying on receive antenna combining [3] before deciding upon the PMI to report and calculating CQI by making some hypothesis on the type of intra-cell interference [4] can be considered as relying on implicit feedback. Schemes like coordinated beamforming (CBF) [5], [6] and SLNR [7] commonly rely on the feedback of the correlation matrix $H^H H$. Such schemes would be classified as relying on explicit feedback since they do not make any assumption on any transmit precoder and do not account for any receive processing in the reported information. However, it is important to note that most transmit filter designs could rely on both implicit and explicit feedback. Schemes in [6] and [7] could be operated based on PMI and CQI feedback, even though the preference would be $H^H H$.

Based on the current literature on the topic [6], [7], we could conclude that CBF/SLNR based on explicit feedback would outperform ZFBF based on implicit feedback. However such conclusions would be very premature as the evaluations have been performed under very ideal assumptions (e.g. ideal link adaptation [2], [5]–[8]). This paper provides a comparative study of implicit vs. explicit feedback for both SU and MU-MIMO. Given the complexity of the system, analytical modeling is not tractable. We therefore resort to realistic system level simulations compliant with 3GPP LTE-Advanced to evaluate the performance of both feedback types.

II. SYSTEM MODEL

We assume a general multi-cell multi-user MIMO system with a total number of $K$ users distributed in $n_c$ cells. If each cell has $N_r$ antennas and each user has $N_t$ antennas, the available number of layers (or data streams) for the network is equal to $\min(K N_r, n_c N_t) = n_c N_t$ when the number of user $K$ is sufficiently large.

Assume that the MIMO channel between the $i^{th}$ cell and the $k^{th}$ user writes as $\alpha_{k,i} H_{k,i}$, where $H_{k,i} \in \mathbb{C}^{N_r \times N_t}$ models the small scale fading process of the MIMO channel and $\alpha_{k,i}$ is the large-scale fading model.

We assume that user $k$ has cell $i$ as its serving cell. We define the served user set of cell $i$, denoted as $K_i$, as the set
of users who have cell $i$ as serving cell.

Transmit beamforming $\hat{x}_i = F_i x_i$ and receive shaping $y_k = G_k y_i$ are respectively performed at the $i^{th}$ cell and $k^{th}$ user where $x_i \in C^{L_i}$ and $y_k \in C^{R_k}$ denote the transmitted and received symbols, and $F_i \in C^{N_i \times L_i}$ and $G_k \in C^{R_k \times N_k}$ denote the predecoding of the $i^{th}$ cell and shaping matrix of the $k^{th}$ user, respectively. Hence, the $j^{th}$ cell serves $K_j$ users with totally $L_j$ layers and the $k^{th}$ user is served with $R_k$ layers such that $\sum_{i=1}^{K_j} L_i = L_j$. The total number of served users writes as $\sum_{i=1}^{K_j} K_i = K$. The received signal of the $k^{th}$ user located in cell $i$ at time $t$ writes as

$$y_k = \alpha_{k,i}^{1/2} G_k H_{k,i,t} F_i S_i^{1/2} x_i + \sum_{j \neq i} \alpha_{k,j}^{1/2} G_k H_{k,j,t} F_j S_j^{1/2} x_j + G_k n_k \tag{1}$$

where $H_{k,i,t} \in C^{N_r \times N_t}$ represents the MIMO fading channel from the $i^{th}$ cell to the $k^{th}$ user at time $t$ and $n_k$ is a complex Gaussian noise $CN(0, N_0 I_{N_k})$. $S_i \in C^{R_i \times L_i}$ is a diagonal matrix that accounts for the power allocation.

Generally speaking, the transmitted symbol vector $x_i$ at $i^{th}$ cell is composed of symbol vector subsets $x_{k,i}$ destined to $k^{th}$ receiver. The received signal of the $k^{th}$ user located in cell $i$ can be further expressed as

$$y_k = \alpha_{k,i}^{1/2} G_k h_{k,i,t} F_i S_i^{1/2} x_i + \sum_{j \neq i} \alpha_{k,j}^{1/2} G_k h_{k,j,t} F_j S_j^{1/2} x_j + G_k n_k \tag{2}$$

where $K_j$ is the served user set of cell $i$ with cardinality $\#K_j = K_i$, $F_k \in C^{N_i \times R_k}$, $S_k \in C^{R_k \times R_k}$, and $x_k \in C^{R_k}$ are submatrices and subvector of $F_i$, $S_i$, and $x_i$, respectively. The first summation expresses the intra-cell (inter-sector) multi-user interference while the second summation refers to the inter-cell (inter-sector) interference. The columns of $F_k$, denoted as $f_k, i, n \in C^{N_i}$, are unit norm i.e. $\|f_k, i, n\| = 1$. $f_k, i, n$ refers to the transmit beamforming vector for layer $n$ of user $k$. Similarly, $g_k, i, n \in C^{N_r \times 1}$ with unit norm, i.e. $\|g_k, i, n\| = 1$, refers to a row of $G_k$ and is the receive shaping vector for layer $n$ of user $k$.

In this paper, we will make the following assumptions for SU-MIMO. First, we assume uniform power allocation among layers as it is usually done in practice. In such case, assuming $L_i$ layers, $S_i = I_{L_i}/L_i$. Second, we assume that each user is only scheduled with 1 layer, i.e. $R_k = 1$. Given such assumption, $F_k$ and $G_k$ boil down to unit norm vectors respectively denoted as $f_k, i, n$, and $g_k, i, n$.

Given the current system model, the actual SINR experienced by user-$k$ layer-$n$ at the time of demodulation $t$ writes as

$$SINR_{k,i,n} = S/(I_i + I_c + O_c + N_0) \tag{3}$$

where $S$ refers to the received signal power of user-$k$ layer-$n$, $I_i$ is the interference between user-$k$ layers, $I_c$ refers to the intra-cell interference (i.e. interference from co-scheduled users) and $O_c$ refers to the inter-cell interference. We can write each term as

$$S = \alpha_{k,i} \|g_{k,n}^T H_{k,i,t} f_{k,i,n}\|^2 E_s / L_i, \tag{4}$$

$$I_i = \sum_{m \neq n} \alpha_{k,i} \|g_{k,n}^T H_{k,i,t} f_{k,i,m}\|^2 E_s / L_i, \tag{5}$$

$$I_c = \sum_{l \in K_i, l \neq i} \alpha_{k,j} \|g_{k,n}^T H_{k,l,t} f_{k,l,t}\|^2 E_s / L_i, \tag{6}$$

$$O_c = \sum_{j \neq i} \alpha_{k,j} \|g_{k,n}^T H_{k,j,t} f_{j,t}\|^2 E_s / L_j, \tag{7}$$

where $E_s$ stands for the transmit symbol energy. Note that in SU-MIMO, $I_c = 0$ and in MU-MIMO with one layer per UE, $n = 1$ and $I_i = 0$. The receive filters $g_{k,n}^T$ are computed as MMSE solutions based on the measurement of the DM-RS of the serving cell and the outer-cell interference.

### III. Implicit Feedback

Implicit feedback fundamentally relies on CQI, PMI and RI feedback. RI is computed as the rank that enables the highest throughput in SU-MIMO transmissions. PMI is a recommended precoder assuming e.g. SU-MIMO transmission with a rank equal to RI. Codebook design for implicit feedback benefits from the fact that the transmit processing and the receiver processing are known at the time of codebook design. Given the objective function (e.g. maximizing channel capacity or minimizing error probability) and the channel distribution, accurate distortion metrics and efficient codebook design criteria can be derived. Assuming LTE Rel. 8 codebook, PMI is chosen as one codeword in that codebook. CQI is computed given RI and PMI. In MU-MIMO, RI could be constraint to e.g. 1, and the reported PMI corresponds to a vector.

The CQI that is reported at time $t' = t - \Delta t$ for user $k$ in cell $i$ and layer $n$ writes as

$$CQI_{k,i,n} = \hat{S}/(\hat{I}_i + \hat{I}_c + \hat{O}_c + N_0) \tag{8}$$

where

$$\hat{S} = \alpha_{k,i} \|g_{k,n}^T H_{k,i,t} \hat{f}_{k,i,n}\|^2 E_s / \hat{L}_i, \tag{9}$$

$$\hat{I}_i = \sum_{m \neq n} \alpha_{k,i} \|g_{k,n}^T H_{k,i,t} \hat{f}_{k,i,m}\|^2 E_s / \hat{L}_i, \tag{10}$$

$$\hat{I}_c = \sum_{l \in K_i, l \neq i} \alpha_{k,j} \|g_{k,n}^T H_{k,l,t} \hat{f}_{k,l,t}\|^2 E_s / \hat{L}_j, \tag{11}$$

$\hat{S}$, $\hat{I}_i$, $\hat{I}_c$ and $\hat{O}_c$ refer to the estimates of $S$, $I_i$, $I_c$ and $O_c$ given the hypothesis that the UE makes at the time of CQI report. $\hat{g}$ is the receive shaping vector (or in other words the antenna combiner) and $\hat{F}_k$ (made of columns $\hat{f}_{k,i,n}$) is the recommended precoder assumed at the time of CQI/PMI/RI feedback. $\hat{F}_{l,t} = \hat{f}_{l,t,1}$ (given the assumption on one layer per UE in MU-MIMO) is the hypothetical precoder for the co-scheduled user $l$ in MU-MIMO. In MU-MIMO, the number
of co-scheduled UEs assumed at the time of CQI calculation is denoted as \( \hat{L} \). In SU-MIMO, \( \hat{L} \) is equal to RI.

\( \hat{O}_c \) significantly depends on the assumptions on the CSI-RS measurement of interfering cells. We assume two kinds of interference measurement at the time of CQI calculation:

- **Subcarrier based interfering CSI-RS measurement** refers to the optimum case where the UE is able to measure the CSI-RS of all dominant interferers at the subcarrier level. Making the hypothesis that the precoder for each interfering link is an identity matrix, i.e. \( \mathbf{F}_j = \mathbf{I}_{n_i} \) with \( \mathbf{F}_j \) the hypothetical precoder for cell \( j \), the UE is able to compute the interference covariance matrix and use that information along with the antenna combiner to perform MMSE filtering at the time of CQI calculation. With such assumptions on the precoder for the interfering links, the estimate of the inter-cell interference \( \hat{O}_c \) writes as

\[
\hat{O}_c = \sum_{j \neq i} \alpha_{k,j} \| \mathbf{g}^\text{T}_{k,n} \mathbf{H}_{k,j,t'} \|^2 / P_s / N_t
\]  

(12)

- **The long term interference measurement** refers to the case where the UE is only aware of the long term average interfering power of the dominant interferers such that

\[
\hat{O}_c = \sum_{j \neq i} \alpha_{k,j} E_s.
\]  

(13)

MMSE filter is then build up assuming the outer-cell interference is a white noise process.

Given that the UE makes some hypothesis (on the transmit precoding, the co-scheduled interference \( \mathbf{f}_{k,i,1} \) and the number of co-scheduled users \( \hat{L}_i \)) at the time of feedback, that the accuracy of the feedback is limited, that the actual precoder will be ultimately computed by the BS and that the channel and the outer-cell interference may have changed between \( t' \) and \( t \), it is very probable that \( \mathbf{f}_{k,i,1} \) and \( \mathbf{g}_{k,1} \) are very different from \( \mathbf{f}_{k,i,1} \) and \( \mathbf{g}_{k,1} \). Given this uncertainty, it is complicated to compute an accurate CQI in MU-MIMO. In SU-MIMO, under stable outer-cell interference, the CQI is relatively accurate given that the intra-layer interference is accounted for at the time of CQI computation and that \( \mathbf{F}_{k,i} = \mathbf{F}_{k,i} \).

LTE Rel. 8 CQI calculation for MU-MIMO consists in assuming no intra-cell interference (i.e. \( \hat{I}_c = 0 \)) and computing the CQI and the antenna combining as in SU-MIMO rank 1 (i.e. \( \hat{I}_l = 0 \)) [4]. The antenna combiner at the time of CQI report is nothing else than the MMSE receiver even given the outer cell interference \( \hat{O}_c \). LTE Rel. 8 CQI for MU-MIMO writes as

\[
\mathbf{CQI}_{k,i} = \hat{S} / (\hat{O}_c + N_0)
\]  

(14)

where \( \hat{S} \) is chosen as in (12) or (13) depending on the interference measurement assumptions.

It is important to note that in a MIMO-OFDM system based on subband feedback, \( \mathbf{CQI}_{k,i} \) is an estimate of the CQI on a given subcarrier. In order to account for the effect of coding over the subband, an effective CQI is computed using some PHY abstraction techniques. The effective CQI is reported to the BS.

### IV. Explicit Feedback

In explicit feedback, the feedback report is not based on CQI/PMI/RI. However there is some equivalence between the reported information in explicit feedback and the CQI/PMI/RI report in implicit feedback. Assume the short term covariance matrix writes as \( \mathbf{H}_{k,j,t'} = \mathbf{V} \mathbf{A} \mathbf{V}^H \). \( \mathbf{V} \) can be reported. The quantization of those eigenvectors and the codebook design does not make any assumption on a specific transmission scheme at the time of quantization. Contrary to implicit feedback, vector quantization for explicit feedback has to be applied without any prior knowledge of the transmit and receiver processing, which complicates the codebook design. In order to perform vector quantization, some distortion metrics have however to be assumed. A typical approach consists in independant quantization of the eigenvectors of \( \mathbf{V} \). We can think off the eigenvectors of the covariance matrix as equivalent to the columns of the PMI in implicit feedback. In the case of perfect quantization, the eigenvectors in explicit feedback and the columns of the reported PMI in implicit feedback are the same.

The eigenvalues of \( \mathbf{H}^H_{k,j,t'} \mathbf{H}_{k,j,t'} \) denoted as \( \Lambda_n \), can be normalized w.r.t. the noise variance and the outer-cell interference \( \hat{O}_c \) based on long term interference measurement as in (13). Normalized eigenvalues in explicit feedback can be thought of as being equivalent to CQI in implicit feedback, hence

\[
\mathbf{CQI}_{k,i,n} = \Lambda_n / (\hat{O}_c + N_0).
\]  

(15)

Note that in a MIMO-OFDM system based on subband feedback, no PHY abstraction is applied at the time of report in explicit feedback, contrary to implicit feedback. To be more rigorous, the computation of the reported information in explicit feedback is based on the average covariance matrix over a subband.

### V. Qualitative Comparisons of Implicit and Explicit Feedback

Based on previous discussions, we can qualitatively draw some major differences between the two feedback types.

The explicit feedback enables the BS to dynamically choose the most appropriate transmission mode and transmit filter. For instance, based on a covariance feedback, the BS can choose the best transmission scheme between SU-MIMO and a MU-MIMO filter designed based on [5]–[7]. In implicit feedback, the transmission schemes are to some extent limited by the presumed/pre-negotiated hypothesis. Less flexibility at the BS is therefore expected with implicit feedback.

In terms of scheduling gain, explicit feedback based on e.g. covariance matrix feedback, is expected to provide more scheduling gain as the feedback provides information about the null space of the channel on top of the signal space. Implicit feedback commonly provides information exclusively about the signal space. Such advantage is usually recognized in the literature focusing on filter designs [6], [7].

The link adaptation is expected to be less accurate with explicit feedback than with implicit feedback, especially when
the report is performed at the subband level as in MIMO-OFDM systems. In explicit feedback, the reported CQI is just an approximation of a normalized eigenvalue (of an average covariance matrix) and does not account for any specific transmit or receive processing. Relying on the reported information at the subband level, the BS has to decide upon the RI and re-compute the CQI based on the actual transmit processing (without any access to the channel at the subcarrier level). The computation of RI and CQI at the BS can be problematic in e.g. SU MIMO. It is especially true given the fact that the BS has no clue about the type of receiver implemented at the UE. In implicit feedback, accurate CQI and RI is available at the UE side if the CQI is matched to a predefined transmission scheme and receiver type. Based on the PHY abstraction, the CQI also accounts for the frequency selectivity of the channel within the subband. Some CQI mismatch is expected if the BS schedules with a different transmission scheme than the one assumed at the the time of CQI computation or if the BS overrides the decisions taken by the UE in terms of e.g. RI.

The uplink overhead is expected to be larger with explicit feedback compared to implicit feedback. The feedback of a covariance matrix requires higher overhead than the feedback of a PMI. Moreover, in some scenarios, unnecessary information is reported in explicit feedback. As an example, reporting a covariance matrix to perform rank-1 beamforming incurs a waste of uplink resource for feedback.

The overall performance in explicit feedback may be improved by the increased switching ability and better scheduling but the lack of accurate CQI and link adaptation may provide some performance loss. In implicit feedback, some performance loss due to less flexibility and scheduling gain is expected but the link adaptation is more accurate and can therefore help overall performance. Rigorous evaluations are performed in the next section.

VI. PERFORMANCE EVALUATION

We consider a FDD-based synchronized network working at 2GHz and compliant with LTE-Advanced. A 10 MHz bandwidth made of 52 resource blocks (RB) is assumed. 19 hexagonal cell sites with 3 sectors per cell and with 500m inter-site distance are considered. 10 users are randomly dropped per sector. Four single-polarized transmit antennas are assumed at the BS and 2 single-polarized receive antennas (separated by 0.5 lambda) at the UE. Spatially uncorrelated (4 lambda spacing and 15 degrees angle spread) and correlated (0.5 lambda spacing and 8 degrees angle spread) deployments are considered at the BS. SCM urban macro based on 3GPP case 1 with 3km/h mobility and 15 degrees down-tilting is assumed.

We perform SU-MIMO with rank adaptation and MU-MIMO based on ZFBF and coordinated beamforming (CBF) [5], [6] with rank adaptation and 1 layer per UE, assuming full buffer traffic. Proportional fair scheduler in both the frequency and time domains is performed. The downlink link adaptation is based on one unquantized CQI and one PMI fed back every 5ms per subband in the case of implicit feedback. For explicit feedback, one or multiple unquantized normalized eigenvalues and the average covariance matrix over a subband or its dominant eigenvectors are reported with the same time and frequency granularity as in implicit feedback. At the BS, the reported CQI(s)/normalized eigenvalues are first scaled up or down based on the outer-loop control. Depending on the statistics of the ACK/NACK feedback, the CQI is updated dynamically at the BS to guarantee a packet error rate of 10%. The vectors $f_{k,i,n}$ at the time of transmission are obtained based on the SU-MIMO or MU-MIMO filter design and the final CQI after filtering is scaled once again based on the normalization of the transmit filter and the actual number of co-scheduled UEs. The MCS level is finally decided.

A subband consists of 4 consecutive RBs. The delay between feedback and transmission is assumed to be equal to 6ms. We assume no feedback errors on the uplink. The PMI/covariance matrix/eigenvectors can be unquantized. In such case it is denoted as 'Perfect CSI' and the reported PMI in MU-MIMO with implicit feedback is equal to the dominant eigenvector of the average covariance matrix over a subband. Perfect CSI in explicit feedback refers to the report of all unquantized eigenvectors of the average covariance matrix. The PMI in implicit feedback can also be quantized using Rel. 8 4Tx codebook (denoted as 'LTE codebook'). In implicit feedback, the eigenvectors are quantized independently using rank-1 LTE Rel. 8 codebook. Localized resource allocation with a scheduling unit equal to 1 subband (4 RBs) is assumed. A non-adaptive and synchronous HARQ based on chase combining with maximum 3 retransmission and 8 ms delay between retransmission is performed. A MMSE receiver based on the ideal measurement of the DM-RS is used at the time of demodulation. The channel estimation on CSI-RS for the measurement and report of CQI/PMI/RI or normalized eigenvalues and covariance matrix or its eigenvectors is also assumed ideal. The PHY abstraction technique is based MIESM (RBIR).

The performance is measured in terms of the average cell spectral efficiency denoted as 'Av. thrpt' and the 5% cell edge spectral efficiency denoted as 'edge thrpt'. Both are measured in terms of bits/s/Hz. In the following tables, FB stands for Feedback.

Table I compares the performance of MU-MIMO in correlated channels. The following schemes are evaluated:

1) ZFBF with perfect CSI and one rank-1 SU-MIMO CQI with subcarrier based interfering CSI-RS measurement (implicit feedback).
2) ZFBF with perfect CSI and one rank-1 SU-MIMO CQI with long term interference measurement (implicit feedback).
3) ZFBF with perfect CSI and the normalized dominant eigenvalue (explicit feedback).
4) ZFBF with LTE codebook (one quantized rank-1 PMI) and one rank-1 SU-MIMO CQI with subcarrier based interfering CSI-RS measurement (implicit feedback).
5) ZFBF with LTE codebook (one quantized rank-1 PMI) and one rank-1 SU-MIMO CQI with long term interference measurement (implicit feedback).
TABLE I

<table>
<thead>
<tr>
<th>No.</th>
<th>Precoding</th>
<th>FB accuracy</th>
<th>FB type</th>
<th>Av. thrpt</th>
<th>edge thrpt</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ZFBF</td>
<td>Perfect CSI</td>
<td>implicit</td>
<td>3.9996</td>
<td>0.1119</td>
</tr>
<tr>
<td>2</td>
<td>ZFBF</td>
<td>Perfect CSI</td>
<td>implicit</td>
<td>3.799</td>
<td>0.1042</td>
</tr>
<tr>
<td>3</td>
<td>ZFBF</td>
<td>Perfect CSI</td>
<td>explicit</td>
<td>3.7252</td>
<td>0.1032</td>
</tr>
<tr>
<td>4</td>
<td>ZFBF</td>
<td>LTE codebook</td>
<td>implicit</td>
<td>3.1606</td>
<td>0.1026</td>
</tr>
<tr>
<td>5</td>
<td>ZFBF</td>
<td>LTE codebook</td>
<td>implicit</td>
<td>3.0605</td>
<td>0.0917</td>
</tr>
<tr>
<td>6</td>
<td>ZFBF</td>
<td>LTE codebook</td>
<td>explicit</td>
<td>2.9548</td>
<td>0.0919</td>
</tr>
<tr>
<td>7</td>
<td>CBF</td>
<td>Perfect CSI</td>
<td>implicit</td>
<td>3.8108</td>
<td>0.1082</td>
</tr>
<tr>
<td>8</td>
<td>CBF</td>
<td>LTE codebook</td>
<td>explicit</td>
<td>2.9909</td>
<td>0.0916</td>
</tr>
</tbody>
</table>

6) ZFBF with LTE codebook (one quantized rank-1 PMI) and the normalized dominant eigenvalue (explicit feedback).
7) CBF with perfect CSI (four unquantized eigenvectors of the average covariance matrix over a subband) and four normalized eigenvalues (explicit feedback)
8) CBF with LTE codebook (two quantized dominant eigenvectors of the average covariance matrix over a subband) and two (largest) normalized eigenvalues (explicit feedback)

From Table I results, we draw the following observations. From No. 1 and 2 and from No. 4 and 5, subcarrier based interfering cells CSI-RS measurement provides additional gains over long term outer-cell interference measurement. From No. 2 and 3 and from No. 5 and 6, we can conclude that for a given filter design and the same assumption on outer-cell measurement, implicit feedback provides slightly higher performance than explicit feedback. Remind that PHY abstraction is applied to implicit feedback but not to explicit feedback at the time of CSI report. From No. 3 and 7 and No. 6 and 8, CBF slightly outperforms ZFBF when the feedback for both schemes rely on explicit feedback. With perfect CSI, from No. 2 and 7, ZFBF with implicit feedback and CBF with explicit feedback have similar performance when the assumption on the outer-cell interference measurement is the same. If we can benefit from more accurate outer-cell measurement (as No. 1), ZFBF with implicit feedback outperforms CBF with explicit feedback. With a quantized feedback, from No. 5 and 8, ZFBF with implicit feedback slightly outperforms CBF with explicit feedback when the assumption on outer-cell interference measurement is the same. If we can benefit from more accurate outer-cell measurement, (as No. 4), additional gain is observed for ZFBF with implicit feedback.

In conclusions, MU-MIMO with implicit feedback slightly outperforms MU-MIMO based on explicit feedback. Moreover implicit feedback provides a lower uplink feedback overhead. Our conclusions are somehow contradictory to the results in [6], [7] and stress the importance of designing transmit filters and feedback schemes enabling an accurate link adaptation.

Table II compares the performance of SU-MIMO in uncorrelated channels. We evaluate SU-MIMO based on implicit feedback with CQI/quantized PMI using LTE codebook/RI feedback and SU-MIMO based on explicit feedback with independent quantization of the first two dominant eigenvectors of the average covariance matrix over a subband and the feedback of the corresponding 2 dominant normalized eigenvalues. In explicit feedback, the BS has to compute the final transmission rank and the precoder based on the feedback while in implicit feedback the PMI is directly used as the precoder.

We conclude from Table II that SU-MIMO with implicit feedback outperforms SU-MIMO based on explicit feedback. Explicit feedback performance is significantly affected by the transmission rank mismatch. Indeed rank 2 transmission is performed 81% of the time with explicit feedback while it is only 46% with implicit feedback. Such over-estimation of the transmission rank in explicit feedback is explained in part by the fact that the BS takes the decision based on a covariance matrix averaged over a subband. However the rank of an average covariance matrix is always larger than the rank of the channel at each subcarrier level. Given the subband feedback granularity, the BS does not have enough information to compute the appropriate rank and the outer loop cannot cope with that issue since it only adjusts the CQI.

VII. CONCLUSIONS

In this paper, we investigate the performance of SU and MU-MIMO based on implicit and explicit feedback. We show that both feedback types achieve similar performance in MU-MIMO with a slight advantage for implicit feedback. In SU-MIMO, implicit feedback achieves significant performance gain over explicit feedback as the transmission rank with explicit feedback tends to be over-estimated. From an overhead point of view, implicit feedback incurs less overhead than explicit feedback. The results stress the importance of enabling an accurate link adaptation while designing transmit filters and feedback schemes.

REFERENCES