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1. Introduction

At the previous RAN1#59bis meeting in Valencia, the following way forward was agreed upon for feedback enhancements in support of enhanced downlink multi-antenna transmission:

- SU-MIMO is supported
  - Release 8 type of feedback will be extended for 8 Tx antenna configurations
    - CQI/RI are computed assuming that the reported codebook entry is interpreted as a recommended precoder by the eNB
  - Use of other types of feedback are not precluded
- Improved accuracy of spatial feedback should be supported if sufficient performance gains in realistic scenarios are demonstrated for at least MU-MIMO.
- Enhanced MU-MIMO is supported
  - The enhancements are in relation to feedback
  - At least the feedback specified for SU-MIMO can also be applied for MU-MIMO operation

In addition, it was agreed at the RAN1#59 meeting in Jeju that dynamic switching between SU- and MU-MIMO transmissions is possible without RRC reconfiguration. Therefore, it is necessary to have convergence regarding a CSI feedback scheme that is suitable for supporting both SU- and MU-MIMO transmissions. This contribution provides an analysis on CSI feedback enhancement schemes that have been proposed so far and presents our current views on Enhanced MU-MIMO.

2. Views on Explicit CSI Feedback Schemes

First, we acknowledge the potential improvement from the explicit CSI feedback [1],[2]. However, explicit CSI feedback would be a newly introduced technique to LTE-Advanced if supported. Therefore, we anticipate that many issues, such as those given below, will need to be investigated and discussed similar to case with the Rel. 8 PMI based feedback scheme.

- **Feedback scheme**: Eigen-vector based scheme, covariance matrix based scheme, etc.
- **Quantization scheme of explicit channel**: Quantization scheme of channel components, channel vectors, or channel matrices, etc., as well as required quantization bits and subband size.
- **Testing methodology, etc.**

Therefore, there is a strong concern that detailed specifications will not be completed before the freezing of the Rel. 10 functionality and ITU submission. Thus, we consider that the implicit CSI feedback should be focused at least for Rel. 10 because explicit CSI feedback would be a newly introduced technique and the remaining time for Rel. 10 may not be enough to discuss and investigate many issues. We also consider that we should pursue discussion on the potential benefits from

employing the explicit CSI feedback scheme targeting beyond Rel. 10. Therefore, we focus on the implicit feedback to support efficiently Rel. 10 MU-MIMO in the following sections.

3. Views on Extensions to Rel. 8 Implicit CSI Feedback

There have been many proposals to extend Rel. 8 implicit CSI feedback to support efficiently MU-MIMO and/or dynamic switching between SU/MU-MIMO. The proposals may be classified into two groups with different goals. We provide an analysis on several schemes in each group hereafter.

3.1. Reduced Quantization Error

The primary goal of the schemes in this category is to use increased CSI feedback bits to improve the quantization accuracy. This can contribute to improving the performance of both SU- and MU-MIMO, regardless of the traffic conditions and the number of active UEs. A straightforward way to improve the accuracy would be to increase the codebook size. However, this results in a significant increase in the feedback overhead. Therefore, many schemes were proposed to take advantage of certain correlations in the space/time/frequency domain to reduce the feedback information while increasing the "effective" codebook size. In what follows, we discuss several approaches in this category.

- **Adaptive codebook [3]-[6]**

  This approach assumes that the long-term spatial correlation matrix is known at both the eNB and UE in our understanding. The correlation matrix or its estimation may be obtained at the eNB by infrequent feedback such as the principal eigenvectors of the correlation matrix from the UE or by estimation from the uplink sounding signals assuming channel reciprocity at the channel statistics level [4]. The main idea is to transform dynamically a fixed baseline codebook into an adaptive codebook by using the spatial correlation matrix. The transformed adaptive codebook is then used at both the eNB and UE for exchanging the Rel. 8 implicit feedback information RI/PMI/CQI. As the baseline codebook, any codebook may be used. Thus, the Rel. 8 codebook could also be reused for this approach, although further codebook optimization would be possible. The adaptation can be done as a function of the spatial correlation matrix, and for example, an effect similar to long-term eigen beamforming can be obtained.

- **Multi-granular feedback [7]**

  This approach uses two types of codebook: one for tracking the long-term and another for tracking the short-term property of the channel. The idea is to compress the channel using the long-term codebook in a lower dimension, whose variation is then tracked using the short-term codebook. To be more specific, let us denote the number of antennas at the eNB and UE as N_{Tx} and N_{Rx}, respectively, then, the UE feeds back (M, $\mathrm{PMI}_{\mathrm{long}}$) infrequently and (RI, $\mathrm{PMI}_{\mathrm{short}}$, CQI) frequently similar to the Rel. 8 feedback where $\mathrm{RI} \leq M \leq N_{\mathrm{Tx}}$. The eNB can compute a product precoder or Kronecker precoder based on the two types of feedback information [7].

  This approach has certain similarity to the above mentioned adaptive codebook approach in that it transforms the channel using the long-term information and then tracks the transformed channel on a short-term basis. One essential difference is that the multi-granular feedback approach compresses the channel in a lower dimension $M \leq N_{\mathrm{Tx}}$ such that the short-term property may be tracked using finer quantization granularity. On the other hand, this would require multiple short-term codebooks to be defined since the dimension of the precoder is effectively reduced from $N_{\mathrm{Tx}} \times \mathrm{RI}$ to $M \times \mathrm{RI}$ and $1 \leq M \leq N_{\mathrm{Tx}}$.

- **Differential feedback [6], [8], [9]**

This approach performs successive refinements of quantization by taking advantage of spatial correlations in the time/frequency domains. By feeding back only the differential information, finer granularity of quantization may be possible without increasing the feedback overhead, if the channel does not change excessively in the time/frequency domains. As is well-known, differential feedback is prone to error propagation. In [10] and [11], differential feedback is also presented aiming at improving the accuracy of channel vector quantization in an explicit feedback context.

- **Codebook download [12]-[15]**

  This approach semi-statically determines a codebook based on channel statistics and downloads it to the UE. Based on the downloaded codebook, the UE computes the Rel. 8 type of feedback RI/PMI/CQI. Three different ways are proposed to achieve the codebook download. One method is called codebook selection where multiple codebooks with individual IDs are pre-defined and eNB signals only a codebook ID to the UE. This requires a small signaling overhead, but it has a limited adaptability. The second method is to compute semi-statically the codebook and download the whole codebook data to the UE. This naturally brings a maximum degree of adaptability, but the signaling overhead can be large. Yet another method is somewhat in between the two methods above. It assumes a certain model with some parameters to describe codebooks. Then, only the model parameters are downloaded to the UE. Although a not-so-large signaling overhead is needed, additional processing is necessary to generate the codebook and choosing the proper model might be difficult.

- **Variable granularity feedback [16]**

  This approach pre-defines a set of multiple codebooks with different sizes for variable granularities. A codebook can be semi-statically selected from the codebook set according to the UE geometry. A finer granularity of feedback is then possible for UEs with high geometry that may be beneficial since those UEs could mainly benefit from the increased accuracy by MU-MIMO transmission. It, however, needs to store multiple codebooks and support different numbers of feedback bits.

- **Multiple Description Coding [17], [18]**

  This approach is originally intended for explicit feedback, but its extension to implicit feedback may be considered. Multiple sets of codebooks are defined for different statistics such as spatial correlations. All codebooks that belong to the same set share certain common statistics. Once a codebook set is selected according to the current statistics of the channel on a long-term basis, different codebooks in the chosen set are used at consecutive feedback time instances in a round-robin manner. At the eNB, any single feedback information alone can be used without quantization error reduction or multiple feedback information can be combined to improve the CSI feedback accuracy. Since a large number of codebooks are necessary, either increased storage for predefined codebooks or increased complexity to generate codebooks would be necessary.

3.2. Multiple PMI Reports

The schemes in this category feedback multiple RI/PMI/CQI reports to support efficiently MU-MIMO, but are not intended to reduce the CSI quantization error. The possibility of reusing the Rel. 8 codebook can be considered as an advantage. On the other hand, since the increased feedback bits are not used to improve the CSI quantization accuracy, the additional overhead may not contribute to improving the performance of SU-MIMO. In the following, we discuss two approaches that have different goals.

- **Best/Worst Companion PMI [19]-[21]**

This approach extends the Rel. 8 PMI/CQI feedback with an extra interference indicator to find the best co-scheduled UEs. The indicator comprises $PMI_c/\Delta CQI$ where PMI_c denotes the best/worst companion PMI and ΔCQI is the SINR loss when the companion PMI_c is co-scheduled. On one hand, this is a straightforward extension of the Rel. 8 feedback mechanism with relatively low additional complexity. On the other hand, it increases the feedback overhead and there are some restrictions in obtaining the potential gain such as a small codebook size and high system load for the scheduler to find effectively the best pairs of UEs to be co-scheduled. It would also be difficult for this scheme to coexist with noncodebook based precoder schemes such as ZF MU-MIMO since the final precoder for data transmission is different from that for the measurement/reporting period.

- **Multi-rank PMI/CQI [22]**

  This approach simultaneously sends multiple PMI/CQI pairs with different ranks, each of which is dedicated to SU-MIMO (any rank) or MU-MIMO (limited to Rank 1 or 2). This clear separation of feedback information enables easy support of dynamic switching between SU- and MU-MIMO transmissions.

3.3. Views on Implicit CSI Feedback Schemes for Enhanced MU-MIMO

This section presents our views on implicit CSI feedback schemes for enhanced MU-MIMO within a single-cell based on the analysis given in the previous sections. We note that the UE feedback for CoMP has also been discussed [23], but we consider that the discussion should be separated from that of single-cell UE feedback so not to complicate further the discussion. In the contribution, we focus on only single-cell UE feedback.

Many proposals have been made for extending the Rel. 8 implicit CSI feedback to support efficiently MU-MIMO. We categorized these proposals in two groups and analyzed them. The primary focus of one group is to reduce the quantization error whereas the other group aims at an efficient support of MU-MIMO with multiple RI/PMI/CQI reports. The essential difference between the two groups is whether or not the increased feedback overhead can be used to improve the quantization accuracy.

The best/worst companion approach does not improve the CSI accuracy. Besides, there are some restrictions in obtaining the potential gain for MU-MIMO such as a small codebook size and high system load. Otherwise, the MU-MIMO scheduler may not effectively find the best pairs of UEs to be co-scheduled and the benefits of increased feedback overhead may be limited. On the other hand, since the improved accuracy of the CSI can be beneficial not only for MU-MIMO regardless of the system load but also for SU-MIMO, we consider that it is more desirable to focus on reducing the quantization error at this stage. At the same time, an enhancement should also take into account dynamic switching of SU- and MU-MIMO transmissions.

Considering the limited timeline of Rel. 10, we should avoid too many CSI/CQI feedback options to decrease the testing burden as much as possible. Therefore, an efficient scheme that has a low impact on the specifications may be more desirable. For instance, a codebook design similar to that for Rel. 8 may be preferred considering the long discussions on the Rel. 8 codebook in the past. In the worst case, we need to consider postponing the CSI feedback enhancement to beyond Rel. 10. At this point, we are still open to enhancement approaches regarding Rel. 8 CSI feedback for single-cell MU-MIMO.

4. Conclusions

We consider that the implicit CSI feedback should be focused at least for Rel. 10. We consider that it is more desirable to focus on reducing the quantization error since the improved accuracy of CSI would

be beneficial not only for MU-MIMO but also for SU-MIMO, regardless of the number of UEs and traffic situation. At the same time, an extension should also take into account support for efficient dynamic switching of SU- and MU-MIMO transmissions. Considering the limited timeline of Rel. 10, we should avoid too many CSI/CQI feedback options in order to decrease the testing burden as much as possible. Therefore, an efficient scheme with less of an impact on the specifications may be more desirable. At this point, we are still open to enhancement approaches regarding Rel. 8 CSI feedback for single-cell MU-MIMO.

5. References

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