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Feedback Compression Schemes for Downlink Carrier Aggregation in LTE-Advanced

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***Abstract*—With full channel state information (CSI) available, it has been shown that carrier aggregation (CA) in the downlink can significantly improve the data rate experienced at the user equipments (UE) [1], [2], [3], [4]. However, full CSI feedback in all component carriers (CCs) requires a large portion of the uplink bandwidth and the feedback information increases linearly with the number of CCs. Therefore, the performance gain brought by deploying CA could be easily hindered if the amount of CSI feedback is not thoroughly controlled. In this paper we analyze several feedback overhead compression schemes in CA systems. To avoid a major re-design of the feedback schemes, only CSI compression schemes closely related to the ones specified in LTE-Release 8 and LTE-Release 9 are considered. Extensive simulations at system level were carried out to evaluate the performance of these feedback schemes in various traffic load conditions. Different scenarios were considered to answer the questions of when and why these CSI feedback compression schemes can be applied in CA.**

I. Introduction

Carrier aggregation has been proposed as a technique in LTE-Release 10 a.k.a LTE-Advanced system to enhance the user data rate [1], [2], [3], [4]. By aggregating several component carriers (CCs) together the spectrum available for transmission in downlink LTE-Advanced system can be extended up to 100 MHz [5]. The CCs can be contiguously or non-contiguously aggregated. Currently, for downlink communication intra-band contiguous aggregation of the CC is preferred as only one RF chain should be established in the user equipment (UE). Although using CC can significantly improve the UEs experienced throughput as showed in this paper later on, it comes at the cost of very high Channel State Information (CSI) feedback overhead. The required feedback overhead increases proportionally with the number of active CCs, N, as well as the number of data streams multiplexed in the downlink. This feedback overhead issue could significantly reduce the efficiency of the uplink communication and therefore the CA system performance as a whole.

In this paper we consider CSI compression schemes defined in LTE-Release 8 and the combinations of these to obtain a basic understanding of what would be important in the feedback CSI information for CA systems. This is also desirable with regard to simplifying the implementations and design of CA in LTE-Advanced [6]. It is obvious that there is trade-off between the system level performance and the amount of CSI feedback. Therefore, the CSI compression performance of the proposed schemes and the corresponding system level performance are investigated separately. We then evaluate each scheme and select the best one based on its performance in both domains. Although in principle LTE-Advanced can support an aggregated bandwidth of up to 100 MHz, due to the spectrum scarcity, operators can not afford to obtain this large amount of spectrum. A total spectrum of 40 MHz which is corresponding to N=4 CCs (10 MHz each) or N=2 CCs (20 MHz each) appears to be a reasonable figure both for system deployment and evaluation. A 2x2 multiple input multiple output (MIMO) system with rank adaptation is used as a study case.

The paper is organized as follows. In Section II we analyze several feedback overhead compression schemes and their corresponding compression performances in detail. Section III describes the modeling and simulation assumptions used in the evaluations. In Section IV we evaluate the performance of the reference CA systems where full CSI feedback is assumed. Section V evaluates and analyzes the performance of the system where different CSI compression schemes are configured. The paper ends with conclusions and discussions in Section VI.

II. CSI overhead analysis and different compression schemes

A. Overview of LTE-Release 8 CSI feedback schemes

For closed loop transmission in LTE-Release 8 the UEs are required to feedback the CSI to the evolved Node B (eNB) for packet scheduling, modulation and coding assignment purposes. A common type of feedback used in system performance evaluation is the full CSI feedbacks scheme, where full Channel Quality Information (CQI) and Precoding Matrix Information (PMI) information are fed back. This scheme requires the largest amount of feedback overhead and therefore will be used as reference.

Normally both the frequency selective CQI and PMI values are reported on each group of Physical Resource Block (PRB). The PRB has both time and frequency dimensions. In frequency domain the PRB is consisting of 12 consecutive sub-carriers with 15 KHz spacing. In the time domain one PRB lasts for 1ms which corresponds to one transmission time interval (TTI). In general, the number of PRBs in a PRB group or subband is bandwidth dependent. However, for a fair comparison in the amount of CSI feedback overhead between 2x20 MHz and 4x10 MHz configurations, a PRB group of size 6 is used in the following analysis. The number of PRB and PRB group (nPRBGroup) in a 20 MHz bandwidth are therefore 100 and 17 respectively. When the downlink data for one UE is multiplexed over multiple streams, the required number of CQI and PMI values also increase accordingly. With 4 bits for quantizing the CQI and 2 bits for indexing the PMI in a codebook based 2x2 MIMO system [8] the required bits for one CC in one CQI/PMI update is

$$\underbrace{4 \times 3}_{\text{Wideband CQI}} + \underbrace{4 \times 3 \times 17}_{\text{subband CQI}} + \underbrace{2 \times 17}_{\text{subband PMI}} = 250 \text{ bits} \tag{1}$$

where factor 3 accounts for 2 individual Rank-2 and one Rank-1 CQI. The wideband CQI is assumed to be included in the periodic feedback, physical uplink control channel (PUCCH). While the frequency selective CQI and PMI are transmitted on the physical uplink shared channel (PUSCH) together with the uplink data.

For 10 MHz bandwidth, the required number of bits for feedback per CC is:

$$\underbrace{4 \times 3}_{\text{Wideband CQI}} + \underbrace{4 \times 3 \times 9}_{\text{subband CQI}} + \underbrace{2 \times 9}_{\text{subband PMI}} = 138 \text{ bits} \tag{2}$$

It should be noted here that we do not consider any compression technique e.g. differential coding of the CQI and/or PMI in this full CSI feedback mode. The UE is supposed to report detail quantized information of the CQIs and the index of the precoding matrix. The calculation of the feedback bits in eq. (1) and eq. (2) therefore can be used as theoretically ideal references.

The full CSI feedback scheme in Eq. (1) and Eq. (2) requires a lot of uplink resource. It may be a big hurdle to the uplink performance in some transmission schemes especially the CA. Therefore, it is desirable to reduce the feedback overhead. Basically, the compression or reduction in the CSI feedback can be done by using either wideband PMI or wideband CQI instead of using the per subband ones. The answer to the question of to what extent we can compress the CSI feedback without significantly degrading the downlink system performance depends heavily on the transmission configurations and traffic conditions. In LTE-Release 8, several CSI compression schemes or feedback modes have been defined. The details for each of these feedback modes can be found in the corresponding 3GPP specifications [8] and [9]. In Table I, we select and list a number of feedback modes those can be potentially utilized in CA system. Their descriptions and the required number of bits corresponding to each feedback mode are also given in the table.

B. CSI feedback schemes for Carrier aggregation in LTE-Advanced

In order to make the CA system backward compatible for LTE-Release 8 UEs, it is decided that each CC will have an independent layer-1 transmission including the Hybrid automatic repeat request (HARQ) and Link Adaptation (LA) functionalities according to LTE-Release 8 assumptions [7]. The assignment of the CC to the UEs is done at layer-3 where different load balancing mechanisms can be configured. The layer-2 packet scheduling is responsible to schedule the UEs assigned at each CC. The scheduling can be done independently for each CC but also can be done across all CCs in order to improve the fairness among the UEs in the system. Figure 1 shows the structure of a downlink CA LTE-Advanced system where it is basically formed by aggregating several LTE-Release 8 building blocks. The readers are referred to [1], [2], [4], for further detail information on CA and current development of CA in LTE-Advanced.

TABLE I
SUMMARY OF THE CSI (CQI/PMI) FEEDBACK MODES DEFINED IN LTE RELEASE 8/9 FOR SINGLE-CARRIER OPERATION [9] AND ANALYZED FOR LTE-ADVANCED CA

Feedback Modes	**Feedback description**	**Required bits (20MHz/10MHz)**
Full CSI	Per subband CQI and per subband PMI; Note that this mode is a reference mode and it is not specified in LTE	250/138
Mode 1-1	Wideband CQI, Wideband PMI	14/14
Mode 3-1	Subband CQI (higher-layer configured) and Wideband PMI	218/122
Mode 1-2	Wideband CQI and Subband PMI	46/30
Mode 2-2	The UEs report the average Best-M CQI (UE selected); the wideband CQI and the Wideband PMI (for the Best-M subbands)	43/35

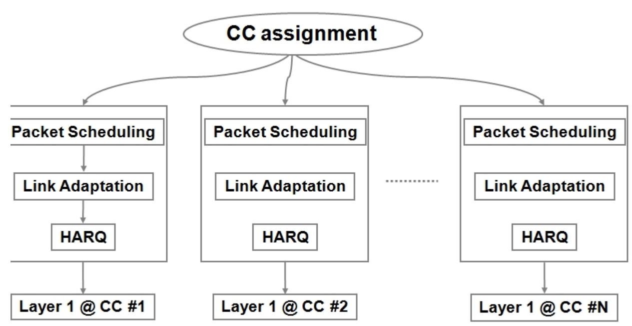

Fig. 1. Structure of a downlink carrier aggregation system

As the basic building block in LTE-Released 8 is utilized in CA systems, it is natural that the CSI feedback scheme for each CC can be selected from any of the CSI feedback schemes defined in LTE-Release 8, Table I. For the sake of configuration simplicity, we propose that a single CSI feedback mode is configured to all active CCs. In this way, the eNB shall select and signal the UEs with only one CSI feedback mode.

C. Feedback CSI overhead reduction analysis

The feedback overhead reductions of different CSI compression schemes for 2x2 MIMO CA systems are illustrated in Figure 2. As for the baseline, it is assumed that 2x2 MIMO UEs always feedback the per subband CSI with dual stream

CQIs and PMIs to the eNB. Since only one LTE-Release 8 CSI feedback scheme is used for all configured CCs, the required number of bits for CA is calculated by multiply the required number of bits per CC (Table I) with the number of active CCs N. From Figure 2 we can see that CQI reporting takes a major part in the feedback overhead. It explains why CSI compression schemes which try to compress CQI information obtain the most feedback overhead reduction. In the feedback scheme Mode 3-1, reporting the wideband PMI instead of the full subband PMI would reduce the feedback overhead by 18% as compared to the full CSI feedback mode. Due to the compression of the CQI, this number is much higher for other feedback schemes where more than 70% reduction in the feedback overhead can be obtained.

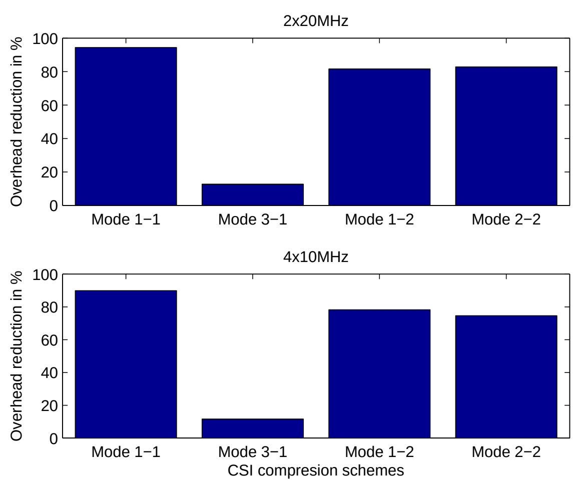

Fig. 2. Overhead reduction obtained by different CSI compression schemes for 2x20 MHz and 4x10 MHz CA configurations

III. Simulation methodology and assumptions

The CSI feedback schemes for CA were evaluated using a downlink multi-cell system level simulator with detail implementation of the layer 3 with CC selection, layer 2 with packet scheduler functionalities as specified in [10]. As the homogeneous Poisson process (birth process) can be used to closely simulate the arrival of new users in the cellular system, we considered a birth-death process traffic model to evaluate the performance of all CSI feedback schemes. LTE-Release 8 UEs is restricted to one CC and the CC with the lowest load (number of users) is assigned to each UE i.e. the least load method [11]. In this way, we can make sure that the number of UEs in each CC is balanced. A round robin mechanism is used at the time domain packet scheduler (TDPS) to select the UEs for further processing at the frequency domain packet scheduler (FDPS). At the FDPS, the UEs are scheduled in a proportional fair (PF) manner. The PF metric is estimated across all CCs to ensure the fairness as proposed in [3]. The performance of two CA systems with 2x20 MHz and 4x10 MHz configurations were evaluated. However, due to the space limitation and the fact that the same observations and conclusions are valid for both CA configurations, we only show the results for 2x20 MHz configuration hereafter. Table II lists the major parameters used in the simulations.

TABLE II
BASIC SYSTEM PARAMETER USED IN THE SIMULATIONS

Parameters	Setting
Test Scenario	3GPP Macro cell case 1, 7 sites, 21 cells with wrap around and only interferences from cells with active UEs are considered
Carrier frequency	2 GHz
Carrier aggregation configuration	2x20 MHz contiguous CCs
CC assignement	LTE-Release 8 UEs: Least Load [11] LTE-Advanced : All CCs
MIMO configuration	2x2 MIMO with rank adaptation
CQI group size	1 CQI per 6 PRBs
CQI reporting error	Log normal with 1 dB std
CQI reporting resolution	5 bits
CQI, PMI reporting delay	5 TTIs
CQI, PMI reporting time	2 TTIs
M value in the Best-M CQI	9 for 2x20 MHz configuration
Time domain packet scheduling	Round Robin
Frequency packet scheduling	Proportional fair across all CCs
1 st BLER target	20%
Traffic type	Burst traffic with fixed buffer size per UE of 16 Mbits and different UE arrival rates
UE population	100% LTE-Release 8 UEs 100% LTE-Advanced UEs
UE arrival rate	1 UE/second/sector to 3 UEs/second/sector
Payload of each call	16 Mbits

IV. Carrier aggregation performance with per subband CQI and PMI

In this section we evaluate the performance of the CA system with LTE-Release 8 UEs and LTE-Advanced UEs where full CSI feedback (per subband CQI and per subband PMI) is assumed. In Figure 3 we show the goodput experienced from the UEs. The 5%-ile (cell-edge), average and 95%-ile (peak) user goodputs are shown on the same figure. Almost two-fold improvement in the user goodput between LTE-Advanced and LTE-Release 8 UEs can be obtained at low offered load. The gain in the experienced goodput of LTE-Advanced UEs over that of LTE-Release 8 UEs gradually reduces as the offered load increases. This behavior can be explained as follows. At low load, the bandwidth available for LTE-Advanced UEs is about N times higher that of LTE-Release 8 UEs. Having more bandwidth to transmit the data, LTE-Advanced UEs outperform LTE-Release 8 UEs in the experienced data rate. As the traffic load increases, more UEs are multiplexed over a fixed amount of bandwidth. Therefore, the total bandwidth resource allocated to LTE-Advanced UEs becomes closer to that of LTE-Release 8 UEs. As a result, the performance difference between LTE-Advanced UEs and LTE-Release 8 UEs gradually becomes insignificant.

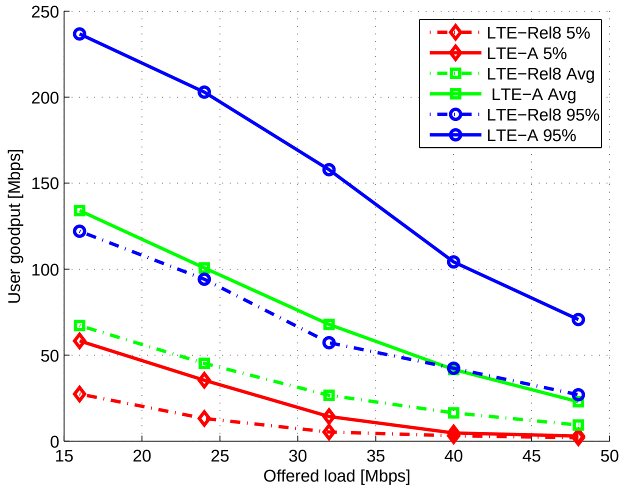

Fig. 3. Data rate experienced at the LTE-Release 8 and LTE-Advanced UEs in different traffic conditions

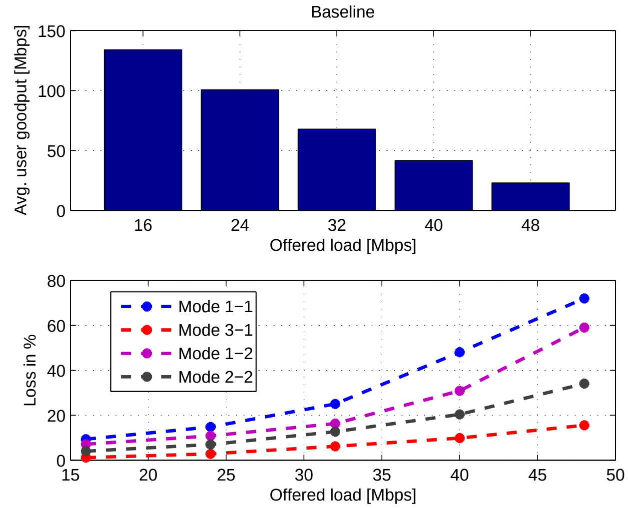

Fig. 4. Average user goodput loss experienced at LTE-Advanced UEs

V. CA PERFORMANCE WITH DIFFERENT CSI FEEDBACK COMPRESSION SCHEMES

Figure 4 shows the degradation in the average user goodput when feedback CSI compression schemes are deployed. LTE system with per subband CQI and PMI feedback was used as the baseline. A general trend we can observe is that the loss increases along with the traffic load of the system. This behavior is adherent to the number of active UEs in the system. When there are only few UEs in the system the inter cell interference level is low and most of the UEs are scheduled for transmission. When the number of active UEs increases, due to the lack of bandwidth resource, only UEs with highest PF metrics can be scheduled. Thereby, the imperfect CSI information leads to sub-optimal, and sometimes even incorrect, scheduling decisions. Consequently, the FDPS gain is severely degraded.

It can be seen from Figure 4 that the performance of the Wideband CQI and Wideband PMI (Mode 1-1) feedback is the worst with the maximum loss of 77%. System with Per Subband CQI and Wideband PMI (Mode 3-1) feedback performs the best with the maximum loss of 20% in the average UE goodput. Being able to reduce the maximum loss from 77% to 30%, the Average Best-M CQI and Wideband PMI (Mode 2-2) feedback scheme outperforms the Wideband CQI and Per Subband PMI (Mode 1-2) feedback scheme. The results indicate that the performance of the system is more sensitive to the CQI feedback information than the PMI feedback information. However, as analyzed in Section II-C, it requires more bits to feedback CQI than to feedback PMI. Therefore, there is a trade-off between the performance of the system and the amount of feedback one can compress.

Figure 5 illustrates the penalty in the 5%-ile user goodput when CSI compression schemes are used. From low to medium system traffic load, the loss increases steadily. It somehow saturates and reaches a floor in the high traffic load region. For cell-edge UEs, the Per Subband CQI and Wideband PMI (Mode 3-1) feedback scheme also gives the best performance. Having frequency selective CQI information could lead to a significant gain as compared to the case of having only wideband CQI information. System with Mode 3-1 feedback scheme can bring down the loss in the cell-edge UE goodput by almost 4 times from the one with wideband CQI and PMI (Mode 1-1) feedback. Therefore in order to obtain a reasonable performance, we should select the CSI compression schemes with feedback of the frequency selective CQI for cell-edge UEs.

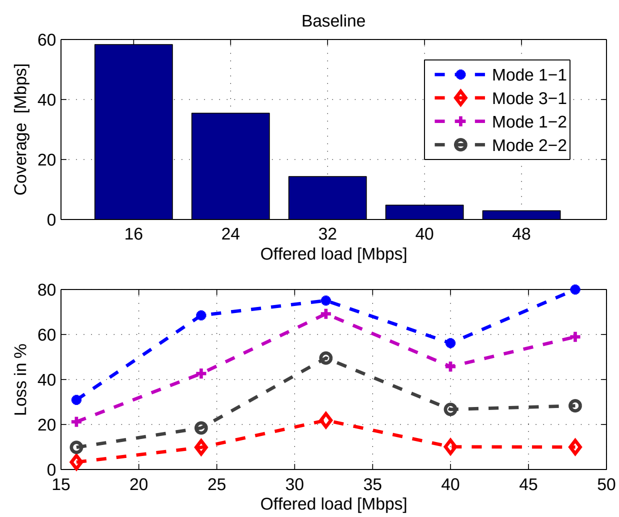

Fig. 5. The loss experienced at the LTE-Advanced UEs in the 5%-ile (coverage) goodput

Figure 6 shows the degradation in the peak UEs goodput for all considered CSI compression schemes. The degradations in performance vs. the offered load follow the same trend as we observe in the average UEs goodput figure. However, it is observed that at low traffic load condition, all CSI compression schemes provide almost the same peak user goodput performance. In this case, due to the low number of active UEs in the system the inter cell interference is limited. The excellent channel condition makes it possible to schedule the UEs in a dual-stream transmission mode most of the time. As the difference between wideband CQI and frequency selective CQI is marginal, wideband CQI information would be enough for the rank adaptation unit to work properly. It explains why the CSI compression schemes with frequency selective CQI feedback do not outperform the schemes with wideband CQI feedback.

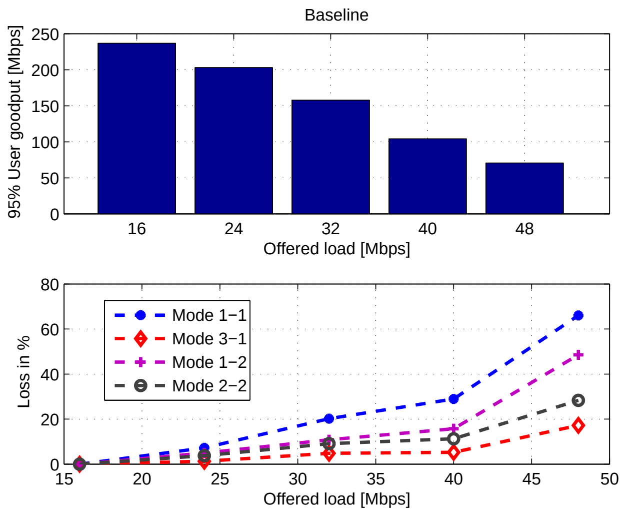

Fig. 6. The loss experienced at the LTE-Advanced UEs in the 95%-ile (peak) goodput

VI. Conclusion and Remarks

In this paper we have analyzed several CSI feedback compression schemes for downlink carrier aggregation in LTE-Advanced system. Reference systems with full CSI feedback were used for performance comparisons. It has been shown that with N active CCs and full CSI feedback, CA can improve the experienced data rate of LTE-Advanced UEs by N times as compared with that of the LTE-Release 8 UEs at low traffic load. However, this gain becomes insignificant in high traffic load conditions.

In order to utilize the defined CSI feedback modes as much as possible and avoid extensive re-designing of the reporting format, we have only selected and evaluated the schemes that are closely related to the basic compression schemes specified in LTE-Release 8 and LTE-Release 9. Moreover, to reduce the signaling complexity, a single CSI feedback scheme is assumed to be configured to all active CCs. The results show that the performance loss due to the compression of the feedback CSI increases along with the traffic load. The presented results highlight that the CSI feedback compression schemes should not be used for cell-edge UEs especially in a high load scenario. For those UEs, it is therefore suggested to configure full CQI and PMI feedback over all CCs. However, as the UEs at the cell-edge often have a poor channel condition, this solution raises a concern on the quality and accuracy of the feedback channel. An alternative could be to assign only a single CC to the cell-edge UEs (as virtual LTE-Release 8 UEs) and increase their scheduling priority in the assigned CC accordingly. From low to medium traffic load, due to their good channel conditions most of the CSI compression schemes can be used for cell-center UEs without significantly degrading their performance. With a suitable CSI feedback mode, the loss in the throughput due to feedback compression of the cell-center UEs can be limited to under 30% at high traffic load condition. In general, for the best trade-off between the overhead compression and user goodput performances it is proposed to use the Average Best-M CQI and Wideband PMI (Mode 2-2) feedback compression scheme.

As for future work, there is room for further development and enhancement. For example, independent configuration of the CSI feedback scheme per CC; designing and configuring CSI compression schemes in parallel with a better load balancing, UEs condition awareness and packet scheduling technique are the subjects of our ongoing studies.

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