Downlink Radio Resource Management for LTE-Advanced System with Combined MU-MIMO and Carrier Aggregation Features

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***Abstract*—In this paper we study the performance enhancement of a downlink LTE-Advanced system with a combination of the multi-user MIMO and carrier aggregation transmission techniques. Radio resource management for the systems with the combined features are proposed, and the system performance is evaluated. Extensive simulations with various traffic load conditions from full buffer with fixed number of UEs to finite buffer with bursty traffic were considered in order to find out when and how these two features can support each other to improve the overall performance gain of the LTE-Advanced system. It is shown that MU-MIMO transmission technique can help to enhance the cell-edge performance of the CA system by 10%-40% depending on traffic load.**

I. Introduction

Being able to utilize the spatial dimensions or multi user diversity of the multiple input multiple output (MIMO) channels, multi user MIMO (MU-MIMO) transmission appears to be a preferred transmission scheme in certain scenarios for example when the number of transmit antennas is higher than that of the receive antennas or when the fading channels among antennas are correlated [1]. Under these conditions, the additional degree of freedom, i.e. multi-user diversity, can help to improve the performance of the MU-MIMO system as compared to the single user MIMO (SU-MIMO) system. Due to the advantage of MU-MIMO, 3GPP Release 8 Long-Term Evolution (LTE) has defined a transmission mode for downlink MU-MIMO transmission, besides the transmission mode SU-MIMO transmission with rank adaptation (RA), [2]. Several advanced features have been added to LTE-Advanced, whereby allowing more advanced receiver implementation and flexible MU-MIMO scheduling. For example, new reference signals have been introduced to support both the demodulation reference symbol (DM-RS) and channel state information estimation (CSI-RS). A new transmission mode, transmission mode 9 (TM9), has been defined which now includes both SU and MU-MIMO transmission capabilities without the need for the user equipment (UE) to be re-configured via higher layer signaling when switching between SU and MU transmission on the shared data channel [4]. However, most evaluations of the MU-MIMO performance in LTE systems are based on the assumption of full buffer condition. It is somewhat a perfect condition with a constant and large number of UEs so that full multi user diversity can be obtained.

As a solution to support very high user data rates in the downlink, carrier aggregation (CA) has been introduced in the LTE-Advanced, [5], [6], [9]. By aggregating multiple component carriers (CC) much larger bandwidth is available. The data rates experienced at the users therefore increase linearly with the number of CCs they are assigned to. The performance enhancement of LTE-Advanced system with UEs capable of operating in several component carriers over the LTE-Release 8 system with UEs operating on single CC has been reported in [8]–[10]. It has been shown that with full buffer mode assumption and fixed number of UEs, there is only marginal improvement in the cell throughput [10]. However, with finite buffer mode and bursty traffic assumptions, at low traffic load the improvement in the experienced user throughput increases linearly with the number of CCs [8], [9]. The gain gradually decreases as the traffic load increases and both LTE-Advanced system and LTE-Release 8 system yields almost the same performance.

Motivated by the observations in this paper we evaluate the performance of a LTE-Advanced system having the two CA and MU-MIMO features coupled. Different traffic conditions were considered in order to find out whether and when MU-MIMO and CA can support each other in reaching the ultimate goal of improving the overall system performance. We focus on the radio resource management functionalities and outline a possible framework for the combined system. The rest of the paper is organized as follows. In Section II, brief overview of the packet scheduler for MU-MIMO and our proposed scheme is presented. The CA concept and our proposed framework for the combination of CA and MU-MIMO in LTE-Advanced system are described in Section III and Section IV respectively. The model and assumptions used in the system level simulations are highlighted in Section V. Performance of the LTE-Advanced system with the CA and MU-MIMO features coupled in full buffer and finite buffer with bursty traffic are presented in Section VI. Section VII wraps up the paper with conclusions and remarks.

II. Multi-user MIMO Packet Scheduler in LTE-Advanced

The packet scheduler for MU-MIMO is often divided into two parts [11]. In the first part, to comply as much as pos-

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sible with the SU-MIMO mode, the same packet scheduling procedure for SU-MIMO is applied, and we have a list of primary MU-MIMO UEs. Selection of the best candidate UEs, which consequently will be paired with the primary UEs, are carried out in the second part. A number of conditions are applied which the candidate UEs should meet in order to be paired with the primary UEs. These conditions are designed to make sure that the overall spectral efficiency will improve after the MU-MIMO transmission. Therefore, when the MU-MIMO transmission scheme is configured, a UE can be scheduled in MU-MIMO mode or fall back to SU-MIMO mode depending on whether the set multi-user UE pairing condition(s) is met or not. Both UEs with first transmission and retransmission can be assigned as primary UEs while only UEs with first transmission are selected as candidate UEs. Our proposed algorithm to find the paired MU-MIMO UEs is described as follows:

Step 1: The SU-MIMO PS procedure with well-known PF algorithm [12] is carried out to find a list of potential primary MU-MIMO UEs. For each i^{th} PRB, the UE that has the estimated throughput in single user mode $\widehat{d}^P > Tmin$ is marked as a primary UE. $Tmin$ is the minimum supported data rate. This condition is used to avoid scheduling the primary cell-edge UE to MU-MIMO mode. UEs who have $\widehat{d}^P \leq Tmin$ are scheduled in SU-MIMO mode.

Step 2: For each i^{th} PRB find the list of MU-candidate UEs with first transmission and sort them according to the following metrics

$$P^i_{MetricMU} = \frac{\widehat{d}^C}{T^C} * (1 - P_{cross}) \quad (1)$$

Where $\widehat{d}^C$ is the estimated throughput of the candidate user scheduled in SU-MIMO mode, T^C is the average delivered throughput to the candidate UE in the past, and P_{cross} is the cross correlation between the precoding of the primary UE and the candidate UE. The rate $\widehat{d}^P$, $\widehat{d}^C$, is estimated from the channel quality indication (CQI) feedback by the UEs.

Step 3: For each i^{th} RPB, perform

If the number of the MU-candidate UEs found in ***Step 2*** > 0 ***Then***

- Select from the list of candidate UEs found in ***Step 2*** has the maximum P^i_{Metric}
- Set MU-MIMO transmission mode to the primary UE and the selected candidate UE

Else

- Set SU-MIMO transmission mode to the primary UE

In order to enable SU and MU dynamic switching and supporting SU-MIMO transmission with up to 8 layers, transmission mode 9 has been defined in LTE-Advanced. According to this transmission mode, it is possible to do rank adaptation (RA) for UEs in SU-MIMO mode. In this paper we consider both systems with rank adaptation and single stream transmission for UEs scheduled in SU-MIMO mode. It may be noted here that MU-MIMO transmission mode is not allowed for multi-stream UEs with retransmission. They are not selected in the MU-primary list in (***Step 1***).

III. Carrier Aggregation concept in LTE-Advanced

By concatenating several CCs together the spectrum available for transmission in downlink LTE-Advanced system can be extended up to 100 MHz. The bandwidth of each CC defines the total number of operating CCs, N. This number can for example range from $N = 2$ CCs to $N = 5$ CCs for a 20MHz bandwidth per CC configuration. 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 [3], [9]. The assignment of the CC to the UEs is done at layer 3 where different load balancing mechanisms can be deployed. Single or multiple CCs will be assigned to the incoming UEs based on their capabilities, requirements on the quality of service (QoS), the load of the system etc. The layer 2 packet scheduling, which consists of time domain (TD) packet scheduling and frequency packet (FD) scheduling, is responsible for scheduling the UEs assigned at each CC. The readers are referred to [5], [6], [9], [10] for further details on current development of CA in LTE-Advanced.

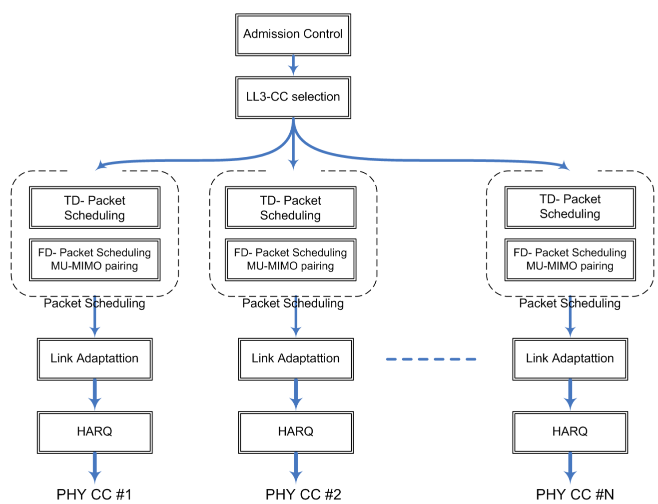

Fig. 1. A framework for combined MU-MIMO and CA transmission and scheduling.

IV. Combination of MU-MIMO with Carrier Aggregation

Since each CC has its own layer 1 to layer 3 implementation, when MU-MIMO and CA features are combined the pairing of MU-MIMO UEs is done independently from CC to CC. In Figure 1 we show the framework of a MU-MIMO and CA LTE-Advanced system. The pairing procedure for MU-MIMO

UEs described in Section II is implemented within the packet scheduling block. The past throughput used in the scheduling metric calculation can be taken from each individual CC. However in order to improve the fairness among UEs in the system, it is suggested to use the UE's past throughput across all assigned CC [7]. The scheduling metrics of the MU-primary UE and the MU-candidate UE at the k^{th} CC and i^{th} PRB are changed to

$$P^{P(k,i)}_{MetricSU} = \frac{\widehat{d}^{P(k,i)}}{\sum_{n=1}^{N} T_n^P}; P^{C(k,i)}_{MetricSU} = \frac{\widehat{d}^{C(k,i)}}{\sum_{n=1}^{N} T_n^C} \tag{2}$$

where $\widehat{d}^{P(k,i)}$, $\widehat{d}^{C(k,i)}$, T_n^P and T_n^C are the estimated throughput and the past throughput of the primary and candidate MU-MIMO UEs respectively.

V. Simulation Methodology and Settings

The performance of combined MU-MIMO and CA features was evaluated using a downlink multi-cell system level simulator with detailed implementation of the layer 3 with CC selection, layer 2 with packet scheduler functionalities [7]–[9]. In the evaluations we considered both the full buffer with a fixed number of UEs in the system and finite buffer with bursty traffic. As mentioned in the introduction Section, LTE-Advanced system with multiple component carriers improves the experienced user throughput especially with low offer load condition in a bursty traffic mode [9]. Therefore, in this paper we are not interested in evaluating LTE-Release 8 system with UEs capable of operating in only one component carrier. Instead, only LTE-Advanced UEs with CA of 2 CCs will be considered. This means that all $N = 2$ available CCs will be assigned to the simulated UEs. Detection of the UE transmitted precoder and the paired UE in MU-MIMO mode is done with the help of the DM-RS. All the overhead related to the DM-RS is taken into account in the calculation of the UE goodput. For illustration purpose we only considered 4x2 MIMO system with up to rank 2 SU-MIMO tranmission. Table I lists the major parameters used in the simulations.

TABLE I
Basic system parameter used in the simulations

Parameters	**Setting**
Test Scenario	3GPP Macro cell case 1, 7 sites, 21 cells with wrap around
Carrier aggregation setting	2x10 MHz intra-band contiguous CCs @2 GHz
Number of PRBs per CC	50 (12 subcarriers per PRB)
CQI, PMI group size	1 CQI, PMI per 6 PRBs
CQI reporting error	Log normal with 1 dB std
CQI reporting resolution	5 bits with 1.6 quantization step
CQI, PMI reporting delay	5 TTIs
Packet scheduling	Proportional fair across all CCs
1 st BLER target	10%
Traffic type	Full buffer, 10 UEs per cell Bursty traffic with 16 Mbits buffer per call and different Poisson arrival rates λ
Inter cell interference model	Full buffer : full interference Finite buffer : only interferences from cells with active UEs are considered
Tx-Rx	4x2 MIMO
Base Station Antenna Setting	3D antenna model, 15^o antenna tilting with 0.5 λ separation and 8^o azimuth spread
MU-MIMO mode	TM9 with and without rank adaptation for UE fall back to SU-MIMO mode
$Tmin$ throughput threshold	512 Kbps

VI. System Level Performance Evaluation

A. Full buffer with fixed number of UEs

We start by looking at the performance of the system with fixed number of UEs and full buffer traffic model. The distribution of the goodput experienced by the UEs with SU-MIMO setting with full rank adaptation (RA SU-MIMO), MU-MIMO setting with single stream transmission for SU-MIMO (MU-MIMO, Rank-1 SU-MIMO) and MU-MIMO setting with rank adaptation for UEs in SU-MIMO mode (MU-MIMO, RA SU-MIMO) are shown in Figure 2. The MU-MIMO scheme with single stream transmission improves the goodput of the UEs at most conditions from the cell-edge to cell-center. For MU-MIMO scheme with RA SU-MIMO, the improvement can clearly be seen for cell-center UEs. Due to the higher estimated goodput for dual stream transmission, $\widehat{d}^{P(k,i)}$ in (2), the cell-center UEs are scheduled more often than the mid-range and cell-edge UEs. As a result, the gain brought by MU-MIMO transmission is more prominent for cell-center UEs than the mid-range and cell-edge UEs.

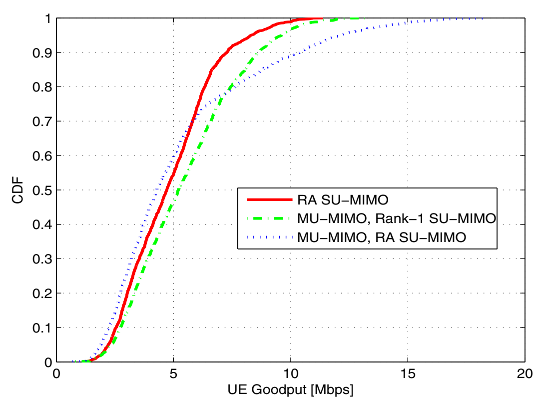

Fig. 2. UE Goodput distribution of SU-MIMO and MU-MIMO systems under full buffer conditions

Figure 3 first row shows the average cell throughput for the MU-MIMO transmission schemes. The SU-MIMO system with the same setting is used as reference. A gain of 13% and 10% is shown to be feasible for MU-MIMO systems with single stream transmission and rank adaptation respectively. It is illustrated in Figure 3 second row that cell-edge UEs can benefit from MU-MIMO transmission even though they are not scheduled in MU-MIMO mode. For MU-MIMO scheme with single stream transmission, a gain of 4%-5% can be obtained for cell-edge UEs. A loss in the cell-edge goodput of 15% is observed for MU-MIMO scheme with rank adaptation. This is due to the bias in scheduling of cell-center UEs as explained

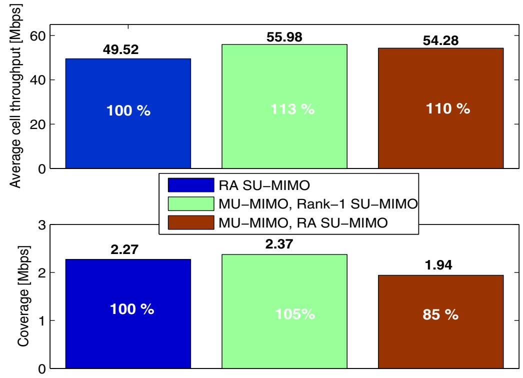

Fig. 3. Average cell throughput and Cell-edge goodput of SU-MIMO and MU-MIMO system under full buffer condition

earlier.

B. Finite buffer and bursty traffic model

Full buffer traffic model with a fixed number of UEs per cell is often used to evaluate the system level performance due to its simplicity. However, it does not closely reflect what happens in a real cellular system where the number of active UEs in the system varies with time. For both CA and MU-MIMO system, being able to model the cellular system with arrival and departure of UEs could reveal the scenarios or conditions where we can get most benefit from these techniques. In this study, we used the birth-death process to model the arrival (birth) and the departure (death) of the UEs. Possion distribution with the arrival rate λ was used to model the birth/arrival process [8].

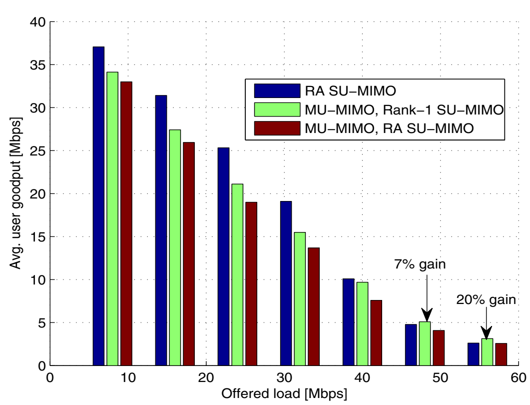

Fig. 4. Average goodput of UEs vs offered load for SU-MIMO and MU-MIMO systems

Figure 4 illustrates the average user goodput of LTE-Advanced systems with the two MU-MIMO and CA features coupled at different offered load. The offered load is calculated as the product of the user arrival rate and the buffer size of the UEs. The performance of LTE-Advanced system with CA and SU-MIMO is also shown for reference. It can be seen that, at low traffic load condition, deploying MU-MIMO in combination with CA system could cause a degradation in the experienced average user goodput. It is true for both the MU-MIMO Rank-1 SU-MIMO and the MU-MIMO RA SU-MIMO. The result is opposed to what we have observed for the full buffer case. The reason for this is the limited number of active UEs in the system. The gain brought by MU-MIMO is prevented by the lack of multi-user diversity. At high traffic load condition, MU-MIMO scheme with single stream transmission enhances the experienced average user goodput by 7% to 20%. Very marginal gain is observed for the MU-MIMO system with rank adaptation and only at very high load.

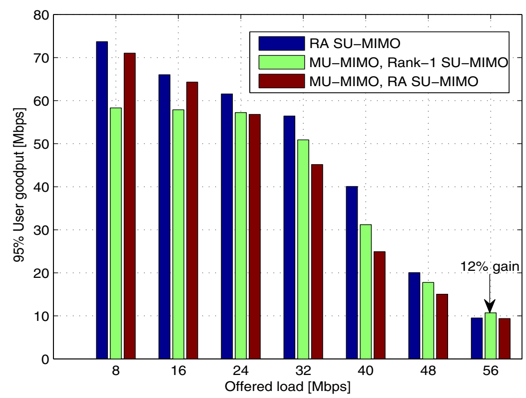

Fig. 5. 95% user goodput of UEs vs offered load for SU-MIMO and MU-MIMO systems

On the contrary, for the peak user goodput, as seen from Figure 5, MU-MIMO with rank adaptation scheme outperforms the MU-MIMO with single stream at low traffic load. At this low traffic load conditions, there will be cases where there is only one UE in the system. As there are not enough UEs for MU-MIMO pairing, this UE will be fall-back to SU-MIMO transmission mode. With the advantage of being able to transmit on dual streams, the MU-MIMO scheme with rank adaptation performs better than the MU-MIMO scheme with single stream transmission. However, from low to moderate traffic load the SU-MIMO scheme outperforms both MU-MIMO schemes. Only when it comes to very high traffic load condition, the MU-MIMO scheme with single stream transmission gives a gain of 12%.

The same trend is observed for cell-edge (5%) user goodput as shown in Figure 6. From low to moderate traffic load, there is no performance enhancement in the cell-edge user goodput for either MU-MIMO schemes. At very high traffic load condition, MU-MIMO scheme with single stream transmission can provide up to 35%-40% gain in the cell-edge user goodput. Again, MU-MIMO scheme with rank adaptation gives very marginal gain.

VII. Discussions

From the observation on the experienced user goodput we suggest to avoid the combination of MU-MIMO and CA from

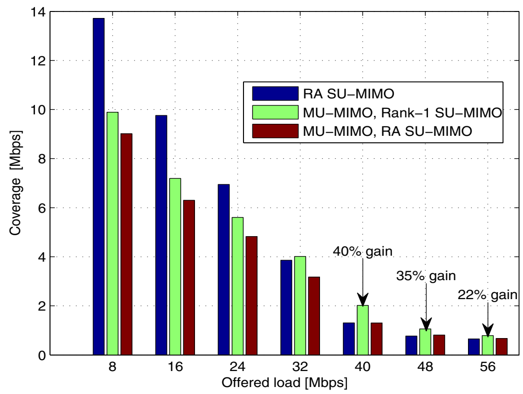

Fig. 6. Cell-edge goodput of UEs vs offered load for SU-MIMO and MU-MIMO systems

low to moderate traffic load conditions where it is better to deploy the CA and SU-MIMO transmission. At high to very high load conditions when there are enough UEs to obtain the multi-user diversity gain, (e.g. more than 7 active UEs per cell according to our results), the MU-MIMO technique could further enhance the performance of LTE-Advanced system by 20%. And both cell-center and cell-edge users benefit from MU-MIMO transmissions. It may be noted here that at this high traffic load, CA does not bring much gain as compared to single carrier transmission [9]. Therefore, the enhancement in the experienced user goodput by implementing MU-MIMO transmission technique at high traffic load is of significant importance.

MU-MIMO transmission can be configured on all active CCs as presented in this paper. This would be a simple case where the traffic loads among component carriers are reasonably balanced e.g. all UEs are assigned to all active CCs. Things are different for the case of unbalanced load due to CA configuration e.g. inter-band CA where lower band CCs are often targeted to cell-edge UEs to improve the coverage and higher band CCs are often targeted to cell-center UEs to improve the cell performance. The configuration of MU-MIMO transmission in this cases should be done independently for each CC as each CC may not have the same number of UEs and more importantly not all cell-edge UEs are suitable for MU-MIMO transmission.

VIII. Conclusion and Remarks

In this paper we have studied the performance of an LTE-Advanced system with combined CA and MU-MIMO transmissions. A 2x10 MHz CA system and a 4x2 MIMO system were used as study case. Different traffic models were used to find out whether and when the combination of these two features would give the maximum performance improvement. We proposed a frequency domain packet scheduling scheme for the selection and pairing of the MU-MIMO UEs and a framework for joint CA and MU-MIMO scheduling.

From the simulation results, it is suggested that MU-MIMO scheme should not be employed in combination with CA in low to moderate load traffic conditions. However, combination of CA and MU-MIMO is highly recommenced for LTE-Advanced system operating in high traffic load conditions when the number of active UEs is enough to obtain the multi user diversity. With MU-MIMO enabled, a gain in the order of 20% in the average user goodput can be achieved as compared with SU-MIMO. Moreover, cell-edge UEs can also benefit from the deployment of MU-MIMO in combination with CA. The experienced user goodput for those UEs can be improved by up to 35%-40% as compared to the SU-MIMO case. For the full buffer and fixed number of UEs traffic model, MU-MIMO can enhance the average cell throughput by 13%. Due to the proportional fair scheduling, enhancement in the cell-center user goodput could also help in creating more bandwidth resource for the cell-edge users. As a result, a gain of 5% can be obtained for cell-edge users even though they may not be scheduled in MU-MIMO mode.

The MU-MIMO scheme with full rank adaptation capability helps to improve the peak user throughput at low traffic load condition only. Therefore it is suggested to deploy MU-MIMO with Rank-1 SU-MIMO transmission to ensure the performance gain. Better utilization of the rank adaption features in MU-MIMO systems, higher transmission ranks e.g. 4 and 8, MU-MIMO transmission configuration for different load conditions and CA setting are the topics of our ongoing research.

Acknowledgement

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