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Downlink Scheduling and Rate Capping for LTE-Advanced Carrier Aggregation

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ABSTRACT

Long Term Evolution (LTE) Carrier Aggregation (CA) was introduced by the Release-10 3GPP specifications. CA allows aggregation of up to 5 cells for a terminal; both downlink (DL) CA and uplink (UL) CA are supported by the 3GPP specifications. However, the first commercial deployments focus on the aggregation of two cells in the downlink. The benefits of LTE CA are increased terminal peak data rates, aggregation of fragmented spectrum and fast load balancing. In this paper, we analyze different strategies of DL scheduling for LTE CA including centralized, independent and distributed schedulers, we provide the corresponding simulation results considering UE data rate limitations and different traffic models. Also, we compare the performance of a single LTE carrier with LTE CA using the same total bandwidth.

Keywords: Long Term Evolution; Carrier Aggregation; Scheduling; Downlink; Bandwidth

1. Introduction

Carrier Aggregation is one of the Long Term Evolution Advanced features introduced by 3GPP in order to meet IMT-Advanced requirements of peak data rates of up to 1 Gbit/s in the DL and 500 Mbit/s in the UL [1-3]. In addition to the User Equipment (UE) peak data rate increase, another benefit of CA is the possibility for operators to aggregate fragmented spectrum. Also fast load balancing can be achieved with LTE-Advanced CA because of a UE with aggregated cells; the traffic can be scheduled on any of the aggregated cells on a Transmission Time Interval (TTI) basis.

The overview of LTE-Advanced CA is given in [4] and [5] while the CA impact on Radio Resource Management algorithms is presented in [6]. In [7], performance results with high number of DL aggregated cells are provided; furthermore, UL CA simulations results are reported in [8]. However, in this paper we focus on the aggregation of two DL cells since this is the first commercial deployment scenario for CA.

The performance of CA is highly dependent on the scheduling method used by the eNode B (eNB). The following three general scheduling principles can be used for CA.

- One centralized scheduler for all aggregated cells.
- Independent schedulers per aggregated cell [9, 10].
- Distributed and coordinated schedulers per cell [9, 10].

In this paper, we compare the above principles taking into account real-life effects such as traffic models and UE data rate limitations. Also, the performance comparison of DL CA with a single carrier of the same bandwidth (BW) is analyzed.

The paper is organized as follows. We discuss strategies for DL scheduling in section 2. Section 3 outlines simulation assumptions. In section 4, we provide the simulation results. Finally, some conclusions are given in section 5.

2. CA Scheduling and Rate Capping Methods

One centralized scheduler serving CA UEs and non-CA UEs of all aggregated cells can potentially offer the optimum performance. The frequency diversity over all aggregated cells can be exploited in scheduling of CA UEs. However, the challenge of this centralized scheduling method is the implementation complexity increased with the number of aggregated cells. In addition to lack of scalability, this method might be not feasible in future inter-eNB carrier aggregation scenarios.

Independent schedulers per aggregated cell represent the simple and scalable extension of single carrier scheduling. This option is expected to have worse performance compared to the centralized scheduling principle because the frequency diversity is exploited separately within each cell. Furthermore, the fairness between UEs can only be achieved and controlled on a cell basis; therefore, this solution is capable of neither achieving nor controlling throughput fairness between CA UEs and non-CA UEs. Also, it shall be noted that in fact the scheduling for CA cannot be fully independent per cell because there are UE data rate limits which shall not be exceeded when allocating resources on multiple cells to a CA UE. Such data rate limits are, for example, the 3GPP defined peak data rate of a given UE category [11] or the amount of UE data available for transmission in the buffer.

The distributed and coordinated schedulers per cell can achieve better performance for Carrier Aggregation compared to independent schedulers [10], the reason being that distributed schedulers can exploit frequency diversity over all aggregated cells in a similar way as the centralized scheduler. In this solution, each cell has its own scheduler; however, as opposed to the independent schedulers, the coordinated schedulers in aggregated cells communicate with each other for the purpose of optimizing scheduling metric calculation. In [9], it is shown that distributed and coordinated schedulers are optimal from the utility maximization point of view. This scheduling method can use the same or similar scheduling metric calculation as the centralized scheduling with the difference that the computation is distributed. The performance of distributed and coordinated schedulers for CA is on a par with centralized scheduling for full-buffer traffic and without considering UE data rate limits. However, if real-life effects like non-full-buffer traffic and finite UE data rate limits (e.g. the peak data rate) kick in, the performance of distributed and coordinated scheduling depends also on the rate capping method used to fulfill the CA UE data rate limits.

In this paper, we consider two methods for rate capping for CA UEs:

1) Static 50/50: the amount of data in the buffer and the peak data rate are divided equally to active serving cells.

2) Dynamic: the amount of data in the buffer and the peak data rate are divided to active serving cells proportionally to the UE throughput achieved on each of the active cells. Additionally, the division of data in the buffer might be adjusted if all data assigned to a given cell is drained in a TTI.

Another relevant topic is the performance comparison of distributed and coordinated CA scheduling with the performance of single-carrier scheduling in the same bandwidth. This comparison is impacted by higher protocol overhead of CA because separate Transport Blocks (TBs) are generated per each scheduled cell. On the other hand, a single cell of a bandwidth equal to the sum of the bandwidths of the aggregated cells will have a worse Channel State Information (CSI) and Resource Block Group (RBG) granularity.

3. Simulation Assumptions

A hexagonal regular cell layout in an urban deployment scenario with 500 m Inter-Site Distance (ISD) was simulated with frequency reuse 1. The deployment area comprises 21 cells placed in a wrap-around model assuming a Typical Urban (TU) channel model. A pathloss model for small cells with PL slope of 37.6 dB per decade was used. Additional penetration loss of 20 dB for indoor coverage was taken into consideration [12]. Basic configuration parameters such as the pathloss model and antenna diagram were selected in accordance to [12].

The number of users within the simulation area was kept constant. Slow-moving subscribers were assumed. During the simulation run, a UE can change its serving cell by handover based on measurements (handover margin 3 dB). The simulation model includes non-adaptive Hybrid Automatic Repeat Request (HARQ) with Chase Combining. The essential simulation parameters are listed in **Table 1**.

4. Simulation Results

4.1. Carrier Aggregation and Single Cell without Physical Downlink Control Channel

In this section, the performances of downlink intra-band CA and single-carrier operation are analyzed without Physical Downlink Control Channel (PDCCH) overhead. To evaluate the cell throughput performance, the same number of UEs (12) per cell scheduler will be set with full-buffer traffic. Other simulation parameters are listed in **Table 2**.

Table 1. Parameters of system simulation model.

Parameters	Settings
Wrap around layout	7 sites with 3 cells/site
Propagation scenario	Macro 1 (ISD 500 m) [12]
Carriers frequency 1	Intra-band: 2 GHz
Carriers frequency 2	Inter-band: 850 MHz and 2 GHz
System bandwidth	CA: 2*10 MHz
Fast fading model	According to [13]
Indoor penetration loss	20 dB (according to [12])
Traffic model 1	Full buffer [14]
Traffic model 2	Constant Bit Rate
UE receiver	2 RX (maximum ratio combining)
UE speed	3 km/h
Scheduler	Proportional Fair
eNodeB power of cell	40 W
Transmission mode	Closed loop MIMO, 2TX
CQI reporting mode	Mode-3
Block Error Rate target	10%

Figure 1 shows the average cell throughput normalized to 10 MHz bandwidth.

CA of two 10 MHz cells uses smaller Resource Block Group (RBG) and Channel Quality Indicator (CQI) granularity compared to a 20 MHz cell. From the simulation result we see that the modified 20 MHz simulation has +3.54% higher cell throughput compared to normal 20 MHz simulation with worse granularity.

Considering the protocol overhead of additional transport blocks and no frequency diversity exploration across aggregated cells, the CA with independent scheduler has -2.32% loss on cell throughput compared to a single 20 MHz cell.

The CA with distributed scheduler is capable to have inter-scheduler communications. It recovers some of the frequency diversity gain from larger bandwidth. The distributed scheduler brings +2.93% higher average cell throughput compared to independent schedulers.

From simulation without PDCCH, CA with distributed schedulers using two aggregated 10 MHz cells can achieve performance similar to a single 20 MHz cell.

Table 2. Settings for CA and single carrier simulations without PDCCH.

Parameters	Single 20MHz	Modified Single 20MHz[a]	CA 2x10MHz Option 1	CA 2x10MHz Option 2
Number of cells	21	21	42	42
Number of UEs per all cells	252 non-CA UEs	252 non-CA UEs	126 CA UEs	126 CA UEs
RBG size	4 PRBs	3 PRBs	3 PRBs	3 PRBs
CQI resolution	4 PRBs	3 PRBs	3 PRBs	3 PRBs
Scheduler	Centralized	Centralized	Independent	Distributed
PDCCH	Disabled	Disabled	Disabled	Disabled

[a] The RBG and CQI resolution granularity is increased in simulation, but not possible by the 3GPP specification according to [15].

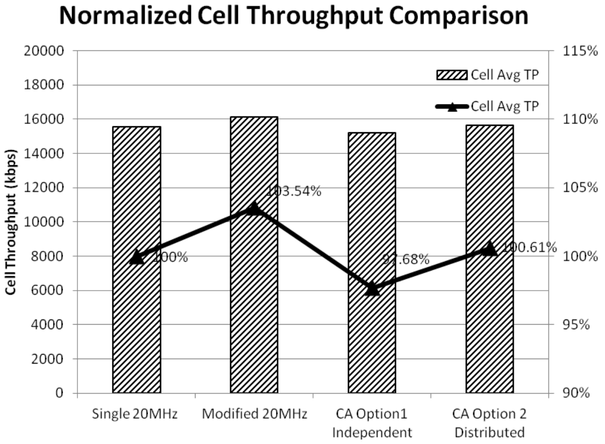

Figure 1. Cell throughput of CA and single carrier without PDCCH.

4.2. Carrier Aggregation and Single Cell with Load-Adaptive PDCCH

In this section, the performances of downlink intra-band CA and a single carrier are analyzed with the modeling of load-adaptive PDCCH. To focus on UE throughput, the same number of UEs (126) in simulation area will be set with the full buffer traffic model. Other simulation parameters are listed in **Table 3**.

Figure 2 shows the average and 5%-ile of UE throughput.

With the PDCCH considered, the performance gap between CA and a single carrier becomes larger. There is -6.98% loss on average UE throughput and -11.39% on 5%-ile UE throughput.

Figure 3 shows the utilization of PDCCH symbols and the utilization of Control Channel Elements (CCEs).

In CA, scheduling of the additional bandwidth requires additional PDCCH assignments. The higher number of orthogonal frequency-division multiplexing (OFDM) symbols for PDCCH reduces the number of OFDM symbols available for data transmission.

Table 3. Settings for CA and single carrier simulations with load adaptive PDCCH.

Parameters	Single 20 MHz	Modified Single 20 MHz[a]	CA 2x10 MHz Option 2
Number of cells	21	21	42
Number of UEs per all cells	126 non-CA UEs	126 non-CA UEs	126 CA UEs
RBG size	4 PRBs	3 PRBs	3 PRBs
CQI resolution	4 PRBs	3 PRBs	3 PRBs
Scheduler	Centralized	Centralized	Distributed
PDCCH	Adaptive	Adaptive	Adaptive

[a] The RBG and CQI resolution granularity is increased in simulation, but not possible by the 3GPP specification according to [15].

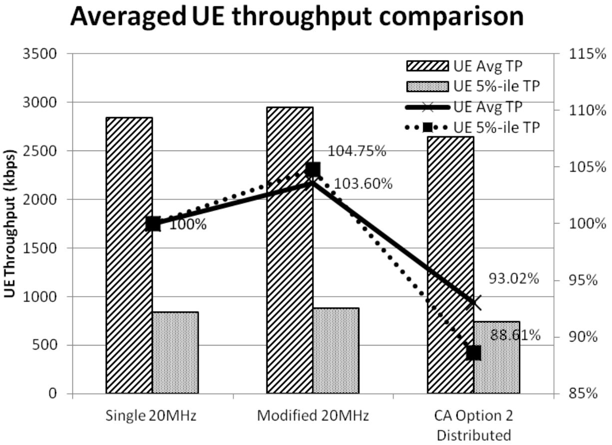

Figure 2. UE throughput of CA and single carrier with load-adaptive PDCCH.

4.3. Rate Capping on UE Buffer

The problem of rate limitation of CA UEs is described in section 2. There are several solutions to rate capping due to the UE buffer, which are investigated in this section; rate capping due to the peak data rate is investigated in section 4.4. **Table 4** lists the solutions to rate capping due to the UE RLC buffer which are compared in our simulation

The simulation assumption for RLC buffer rate capping simulations can be found in **Table 1** with the second traffic model – Constant Bit Rate (CBR) and inter-band CA. Each user has a 1Mb/s CBR service. The simulation results are shown in **Figure 4**.

The simulation results are analyzed in terms of number of allocated Physical Resource Blocks (PRBs) per cell for the CBR service. From the results it can be seen that the ideal mode is the most efficient method for each number users. The dynamic mode is superior to the static mode with 50%-50% split.

4.4. Rate Capping on Peak Data Rate

Table 5 shows the solutions to rate capping due to the UE peak data rate which are compared in our simulation.

The peak data rate of the UE in our simulations is 51.024 Mbps which is based on UE category 2 according to [11].

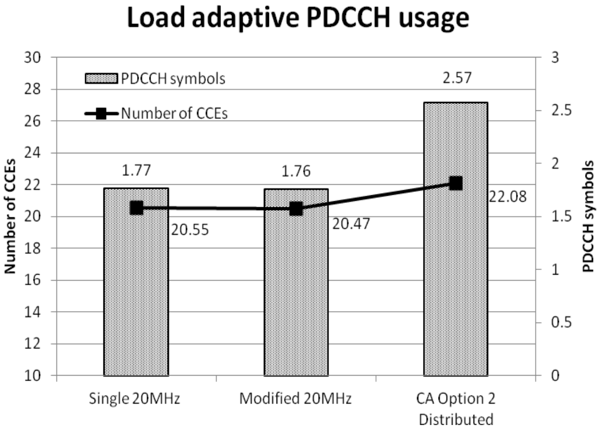

Figure 3. PDCCH symbols of CA and single carrier.

Table 4. Solutions to RLC buffer rate capping.

Solution	Description
Ideal	Close to genie-aided
Static	50% of the RLC buffer allocated to the PCell and remaining to the SCell statically
Dynamic	X% RLC buffer allocated for PCell and (100-X)% for SCell dynamically

The simulation assumption for rate capping due to the UE peak data rate can be seen in **Table 1** with the first traffic model – Full Buffer and inter-band CA. **Figure 5** shows the simulation results.

The simulation results are analyzed in terms of average user throughput for the full-buffer service. From the results it can be seen that the difference between different modes in higher number of users is very small. However, in case of a very low number of users such as 1 or 2, the ideal mode is superior to other modes while the dynamic mode is slightly better than the static mode with 50%-50% split.

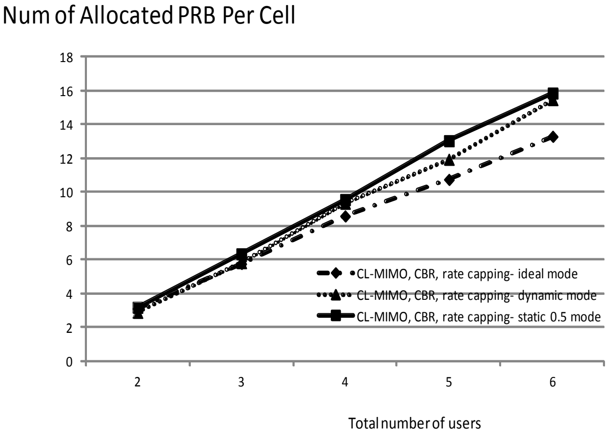

Figure 4. Simulation results of RLC buffer rate caping.

Table 5. Solutions to peak data rate capping.

Solution	Description
Ideal	Close to genie-aided
Static	50% of UE Peak Data Rate allocated to the PCell and remaining to the SCell statically
Dynamic	X% UE Peak Data Rate allocated for PCell and (100-X)% for SCell dynamically

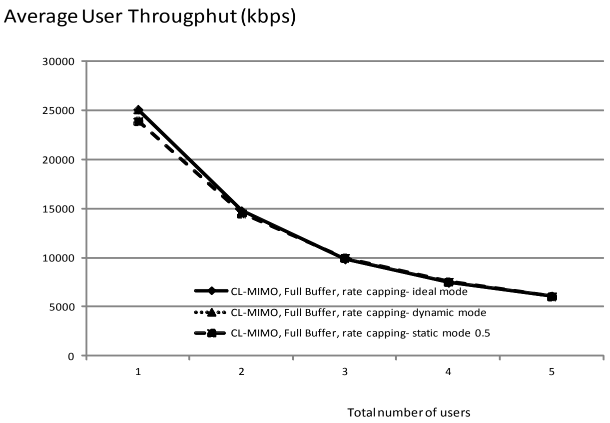

Figure 5. Simulation Results of Rate Capping on Peak Data Rate.

5. Conclusions

In this paper, we discussed and simulated rate capping methods for LTE-A DL Carrier Aggregation scheduling. Such rate capping is required due to non-full-buffer traffic and other practical UE data rate limits when independent or distributed/coordinated scheduling is used for CA. Also, we provided simulation results comparing the performance of CA scheduling methods with a single cell.

Based on the analysis and the simulations in this paper, we draw the following conclusions. Aggregated cells can have spectral efficiency similar to a single cell of the same bandwidth assuming the same number of full- buffer UEs per cell. Distributed and coordinated schedulers provide better performance for DL CA compared to independent schedulers. The analyzed rate capping solutions provide good performance; the dynamic solution outperforms the static solution.

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