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Uplink Component Carrier Selection for LTE-Advanced Systems with Carrier Aggregation

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Abstract— **Carrier aggregation (CA) is one of the key features for LTE-Advanced. By means of CA, two or more component carriers (CCs) can be aggregated to form a much wider transmission bandwidth up to 100 MHz in order to meet the IMT-Advanced requirements. With CA, it is possible to schedule a user equipment (UE) on multiple component carriers simultaneously. From radio resource management (RRM) perspective, CC selection plays an important role in optimizing the system performance with CA. In this paper, we investigate the uplink resource allocation for LTE-Advanced Systems, i.e., how to assign CCs to different users, and how to do the power scaling for each user. A pathloss threshold based CC selection algorithm is proposed to distinguish between power-limited and non-power-limited LTE-Advanced UEs, and assign only one CC to power-limited LTE-Advanced UEs, while assign multiple CCs to non-power-limited LTE-Advanced UEs. Simulation results show that the derived pathloss threshold works effectively and efficiently compared to other thresholds, and the proposed CC selection algorithm can achieve much better performance in terms of cell edge, average, and cell center user throughput compared to blindly assigning all LTE-Advanced UEs on all CCs.**

I. INTRODUCTION

In order to meet the technical requirement defined by IMT-Advanced, which targets to achieve peak data rates up to 1 Gbps in downlink and 500 Mbps in uplink respectively [1], the 3rd Generation Partnership Project (3GPP) started a new study item in March 2008 on evolving from Long Term Evolution (LTE) towards LTE-Advanced with the target of finalizing the Release-10 (Rel10) specifications between the year 2010 and 2011. Carrier aggregation (CA) is one of the key features for LTE-Advanced. By means of CA, users can access a much wider transmission bandwidth up to 100 MHz compared with legacy LTE Release 8 standard (i.e., up to 20 MHz) [2]. This is achieved by using CA to aggregate two or more individual component carriers (CCs) belonging to contiguous or non-contiguous frequency bands [3].

With carrier aggregation, it is possible to schedule a user on multiple component carriers simultaneously, each of which may exhibit different radio channel characteristics. This introduces some new challenging issues related to modifications and completely new functionalities in radio resource management (RRM) framework for LTE-Advanced systems supporting multiple-CC operation, thus is an area of research interests. The downlink performance of CA over deploying independent carriers is investigated in [4]. The simulation results show that CA can enhance the throughput, fairness and latency compared with independent carrier scenario for different traffic models. Different load balancing methods for allocating users to CCs are analyzed in [5] by means of theoretical formulation as well as simulations. Also a cross-CC packet scheduling algorithm was proposed to improve the coverage performance. However, most of the existing work on CA in LTE-Advanced systems are concentrated on the downlink. One of the main differences between uplink and downlink is the transmission power constraint of a user equipment (UE). In uplink, allocating more CCs to a UE does not necessarily result in a performance gain as in downlink. Therefore, it is not a good idea to always allocate multiple CCs to LTE-Advanced UEs, especially to those power-limited UEs that experience unfavorable channel conditions. The uplink performance of CA is investigated in [6] with different power back-off settings. The results show that with proper CC allocation, substantial performance gains can be achieved in terms of average and cell center user throughput. But no details of how to allocate CCs to different UEs are given in [6]. The objective of this paper is to design a smart CC-selection algorithm that can optimize the system performance with CA in uplink.

The rest of the paper is organized as follows. Section II gives a general overview of the most important RRM functionalities in uplink CA for LTE-Advanced systems, with special attention on CC selection together with uplink power control. Section III outlines the simulation methodology and main assumptions. Simulation results and performance comparisons are presented in Section IV. Finally, some conclusions are drawn in Section V.

II. RADIO RESOURCE MANAGEMENT

The RRM framework for multi-component carrier LTE-Advanced system is illustrated in Fig. 1. Separate RRM blocks operate independently on each component carrier. It has been agreed within 3GPP working group to adopt independent Link Adaption (LA) and Hybrid ARQ (HARQ) per CC in coherence with LTE Rel'8 assumptions [3]. Such strategy maintains the backward compatibility so that an LTE Rel'8 terminal can work in an LTE-Advanced system. The admission control module in base station decides whether an incoming connection should be accepted or not. Then the CC selection module allocates one or multiple CCs to the incoming user based on the Quality-of-Service (QoS) requirements, terminal capability, etc. For the packet scheduler, since a user may be

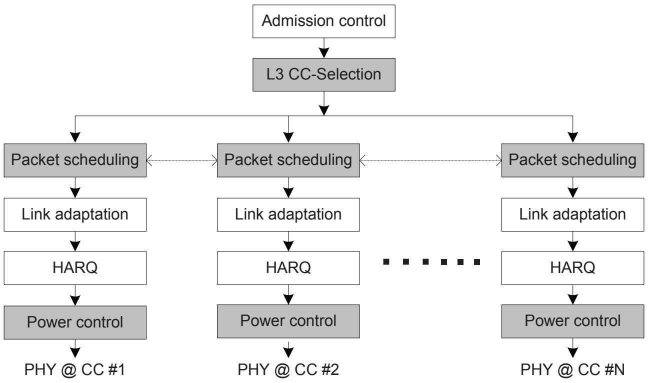

Fig. 1. RRM framework of a multi-component carrier LTE-Advanced system

scheduled on multiple CCs, the per-CC time and frequency domain packet scheduler should support joint scheduling [5], e.g., exchanging the information of average user throughput across multiple assigned CCs to achieve better performance in terms of user fairness and cell coverage. Since the UEs are limited by the maximum transmission power, power control is also an important issue in uplink. Some of the key functionalities to be addressed in this paper are highlighted in grey.

A. CC Selection and Load Balancing

The main difference of LTE-Advanced RRM framework compared to Rel'8 is the CC-selection functionality which is responsible for configuring a CC set for each user. A primary component carrier (PCC) is assigned to each UE and can only be changed via handover. Apart from the PCC, the UE may be configured with one or more additional UL and DL CCs, which are called secondary component carriers (SCCs). These secondary CCs can be activated/deactivated by signalling [2]. In a multi-CC LTE-Advanced system, both Rel'8 and LTE-Advanced users may co-exist. The legacy Rel'8 users can only be assigned on one CC, while LTE-Advanced users can be assigned on multiple CCs. The CC-selection functionality is important to perform load balancing among CCs, as well as to optimize the system performance.

For optimal system performance, it is desirable to distribute the load equally on each CC, so a simple yet effective Round Robin (RR) load balancing scheme is applied, which selects the CC with the least number of users for Rel'8 users. LTE-Advanced users can be assigned on multiple CCs. A simple solution is to assign all CCs to LTE-Advanced users. In downlink, allocating more CCs to an LTE-Advanced user generally results in a higher throughput thanks to the larger transmission bandwidth and higher transmission power. However, this is not always the case in uplink. The main difference between uplink and downlink is the transmission power constraint of a UE. For power limited cell edge users, even if they are assigned on multiple CCs, they do not have sufficient power to explore the increased transmission bandwidth. Furthermore, when a UE is transmitting over multiple CCs, it requires additional power back-off since the SC-FDMA properties of Release 8 are not maintained. Studies have shown that transmission over multiple CCs will result in an increase of peak-to-average power ratio (PAPR) and cubic metric (CM). This in turn introduces additional reduction of maximum UE transmission power in order to operate in the linear region of the power amplifier [7]. For power limited users transmitting at (or close to) maximum transmission power, such cost might counterbalance the gain brought by multiple-CC transmission, and even results in a performance loss compared to the case where the SC-FDMA properties of the transmitted signals are maintained (single CC assignment). Another major drawback of configuring multiple-CC transmission is the control channel issues. With channel-aware packet scheduling and link adaptation been applied, certain transmission resources are required to provide the eNodeB with knowledge of channel state information between the eNodeB and UE via sounding in uplink. If a user is allocated on multiple CCs and sounding is reported on each CC, it may lead to very high overhead. Therefore, a smart CC-selection algorithm should be carefully designed to achieve the optimal performance in uplink.

B. Proposed pathloss-threshold based CC Selection

The basic idea behind the proposed pathloss-threshold based CC-selection algorithm is to distinguish between power-limited and non-power-limited LTE-Advanced UEs, and assign only one CC to power-limited users, but may assign multiple CCs to non-power-limited users. As the UE transmission power is mainly determined by the path loss, one possible solution to distinguish between power-limited and non-power-limited UEs could be based on a path loss threshold.

We assume that eNodeB is deploying Load Adaptive Power Control (LAPC) independently on each CC. Previous studies [8] show that system performance in terms of coverage and cell throughput is highly dependent on the setting of P_0. However, the optimal setting of P_0 depends on the average allocated bandwidth per UE. As a result, for load-varying systems, it is not possible to set a static value of P_0 and expect it to perform optimally under various traffic conditions. Therefore, LAPC algorithm is proposed to dynamically adjust the users' power spectral density using either P_0 or closed loop corrections. If the optimization goal is to maximize the coverage (5-percentile user throughput), the 5-percentile cell edge users should transmit with the maximum transmission power. Then the power control parameters are set according to the following equation:

$$P_{0,k} + f(\Delta_{i,k}) = P_{\max} - 10\log_{10}\widetilde{M}_k - \alpha_k \cdot L_{95\%} \qquad (1)$$

where $\widetilde{M}_k$ is the average number of allocated physical resource blocks (PRBs) on component carrier k, $P_{0,k}$ and α_k are CC-specific open loop power control parameters, $P_{\max}$ is the maximum UE transmission power in dBm, $L_{95\%}$ is the estimated 95-percentile user path loss in the corresponding cell (not CC-specific since we assume contiguous CA), and $f(\Delta_{i,k})$ is the closed loop power control correction for user i on component carrier k.

The pre-allocation of transmission power on each assigned CC depends on the UEs' metrics and the scheduling algorithm. In this study we adopt an adaptive transmission bandwidth (ATB) packet scheduling algorithm which tightly couples the bandwidth allocation and packet scheduling together to exploit the envelope of UEs' metrics [9]. The algorithm first selects a UE with the highest metric and then expends its transmission bandwidth until either another UE has a higher metric on the adjacent PRB or the maximum transmission power of a UE is exceeded. With LAPC on each CC, the average transmission power of user i on component carrier k can be expressed as:

$$P_{i,k} = 10\log_{10} M_{i,k} + P_{0,k} + f(\Delta_{i,k}) + \alpha_k \cdot L_i \qquad (2)$$

where $M_{i,k}$ is the number of allocated PRBs of user i on component carrier k, and L_i is the path loss of user i.

Then for an LTE-Advanced user i assigned on multiple CCs, the total transmission power should not exceed the maximum power limit:

$$P_i = 10\log_{10}\left(\sum_{k=1}^{K} 10^{P_{i,k}/10}\right) \leq P_{\max} - P_{\text{backoff}} \qquad (3)$$

where K is the total number of allocated CCs for user i, and P_{backoff} is the estimated power back-off in dB to model the effects of increased PAPR and CM when a UE is transmitting over multiple CCs simultaneously. The value of P_{backoff} depends on several factors (such as the number of allocated CCs, size of the clusters, frequency separation between the clusters, modulation and coding schemes, etc.) thus is a complex issue. In this study, to simplify the analysis, we assume that if a UE is scheduled for transmission only on one CC, there is no power back-off, otherwise, it is set with a fixed value.

Inserting (1) and (2) into (3) and assuming $M_k = M_{i,k}$ and same α on each CC, we obtain the path loss threshold:

$$L_{\text{threshold}} = L_{95\%} - \frac{10\log_{10}(K) + P_{\text{backoff}}}{\alpha} \qquad (4)$$

Based on the derived path loss threshold, we propose a new CC-selection algorithm in uplink CA. LTE-Advanced users whose path loss is lower than the threshold are considered to be power-limited and are assigned only on one CC, otherwise they are considered to be non-power-limited and are assigned on multiple CCs. The proposed CC-selection algorithm is illustrated in Fig. 2.

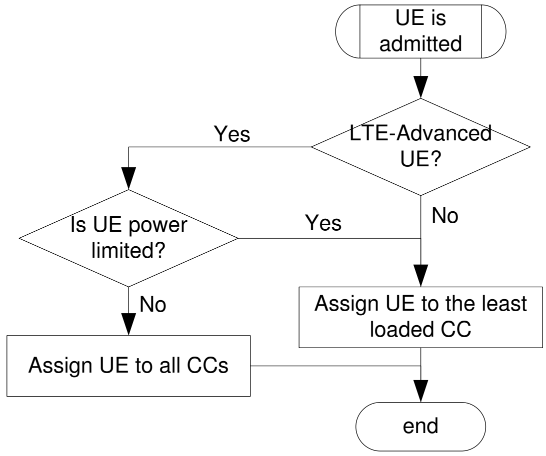

Fig. 2. Proposed CC-selection algorithm for LTE-Advanced system

III. Simulation Assumptions

The performance evaluation is based on a detailed multi-cell system level simulator which follows the guidelines in [12]. The simulation scenario is 3GPP Macro-cell case #1 with 7 sites and 3 sectors per site using the wrap-around technique. Two contiguous component carriers, each with 20 MHz bandwidth, are configured to form a wide band of 40 MHz. Two types of UEs, i.e., Rel'8 UEs and LTE-Advanced UEs, are supported in the system. Rel'8 UEs are only assigned on one CC with RR load balancing, while LTE-Advanced UEs can be assigned on one CC or both CCs depending on the CC-selection algorithm. The link to system level mapping is based on the actual value interface (AVI) method [13]. It is assumed that distance-dependent path loss and shadowing are maintained constant for each UE, but fast fading is updated every TTI independently on each CC based on the ITU Typical Urban power delay profile and UEs' speed. A dynamic traffic model with Poisson arrival per cell is assumed, each call having a finite buffer of 2 Mbits payload. The offered load per cell can be obtained by multiplying the user arrival rate with the payload size. Proportional fair scheduling in frequency domain is used together with adaptive transmission bandwidth allocation. Same open loop power control settings are applied on each CC, while independent LAPC is enabled on each CC to dynamically update the value of $P_{0,k}$ periodically. The effects of increased PAPR and inter-modulation when a UE is transmitting over multiple CCs simultaneously are modeled by a power back-off parameter P_{backoff} with 4 dB power back-off. Table I summarizes the main parameter settings used in the system-level simulations.

IV. Simulation Results

We start our analysis by evaluating the effectiveness of the derived path-loss threshold. Fig. 3 shows the the cell edge and average user throughput versus different values of path-loss thresholds in both low traffic (10 Mbps offered load) and high traffic conditions (20 Mbps offered load). We assume 100% LTE-A UEs with 4 dB power back-off. The cell edge user throughput stays almost constant when the path-loss threshold is higher than a certain point (approximately around -120 dB). Before that point, the cell edge user throughput decreases as the path-loss threshold decreases. For the average user throughput, it increases as the threshold increases until the maximum value is reached at certain point (also around -120 dB), then the throughput decreases with the increase of threshold. In our proposed CC-selection algorithm, LTE-A UEs are assigned only on one CC if the UE's path-loss is lower than the threshold, otherwise it is assigned on both CCs. If the threshold is set to be high, most LTE-A UEs, including

Parameters	Settings
Propagation scenario	Macro case #1
Layout	7 sites - 3 sectors/site - wrap around
Component carriers	2×20 MHz contiguous @ 2GHz band 92 available PRBs per CC
eNode-B receiver	2-Rx MRC
UE bandwidth	ATB: [1, 92] PRBs per CC
Packet scheduling	Proportional Fair with ATB
Traffic model	Finite buffer with Poisson arrival Fixed file size of 2 Mbits per UE Offered load: $[5:5:35]$ Mbps
Available MCSs	BPSK (R=1/5,1/3) QPSK (R=1/4,1/3,1/2,2/3,3/4) 16QAM (R=2/3,3/4,5/6)
α	0.6
P_0	LAPC
$P_{\max}$	200 mW [23 dBm]
P_{backoff}	4.0 dB
HARQ	Synchronous Non-adaptive
BLER target	30%
Link adaptation	Fast AMC
CSI resolution	2 PRBs
CSI error statistics	$\mu = 0$ dB and $\sigma = 1$ dB

TABLE I

SUMMARY OF MAIN SIMULATION PARAMETERS

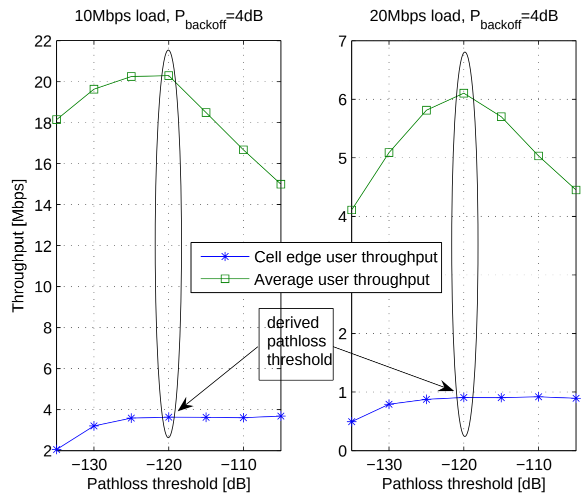

Fig. 3. Cell edge and average user throughput under different path-loss threshold, 10 and 20 Mbps offered load, $P_{\text{backoff}} = 4$ dB

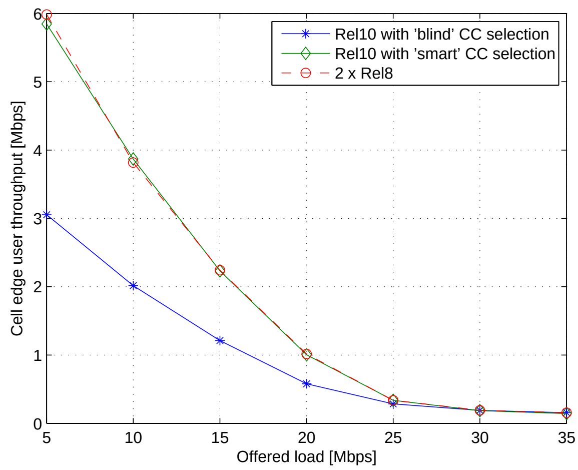

Fig. 4. Cell edge user throughput under different traffic loads in different scenarios, $P_{\text{backoff}} = 4$ dB

power-limited and some non-power-limited UEs operating not close to their maximum transmission power, are only assigned on one CC. As a result, those non-power-limited LTE-A UEs can not benefit from the advantages of transmission bandwidth expansion by using CA. Therefore, if the threshold value is set to be high, the average user throughput decreases, while the cell edge user throughput remains steady since the cell edge UEs usually experience high path-loss and they are assigned only on one CC. On the other hand, if the threshold value is set to be low, not only non-power-limited but also some power-limited LTE-A UEs are assigned on both CCs. As a result, those power-limited cell edge LTE-A UEs will experience performance loss from being scheduled over multiple CCs due to the further reduction of maximum UE transmission power when transmitting over multiple CCs. Therefore, both the cell edge and average user throughput decreases if the threshold is set to be low. So the value of path-loss threshold has to be carefully calculated in order to optimize the system performance. It is shown from Fig. 3 that our derived path-loss threshold can achieve the optimal performance in terms of cell edge as well as average user throughput under different traffic conditions. Thus is robust against traffic loads.

Since CC selection is critical on the overall system performance, next we evaluate and compare the performance of proposed pathloss-based CC-selection algorithm with other CC-selection algorithm, e.g., 'blind' CC-selection (all LTE-A UEs are assigned on all CCs). Fig. 4 shows the cell edge user throughput versus the offered load with 4 dB power back-off in different scenarios. It is shown that if all LTE-A UEs are assigned to both CCs, there is a performance loss at cell edge compared with Rel'8 case. This is because at the cell edge, UEs usually experience high path loss and are limited by the maximum transmission power. Transmitting over multiple CCs will cause further power reduction due to the effect of increased PAPR. Therefore cell edge LTE-A UEs will experience performance loss if they are assigned on multiple CCs, and the loss will be even worse with the increase of power back-off. In the proposed pathloss-based CC-selection algorithm, cell edge LTE-A UEs are only assigned on one CC, so there is no performance loss at cell edge compared with Rel'8 case, regardless of the setting of power back-off.

Fig. 5 shows the average user throughput versus the offered load with 4 dB power back-off in different scenarios. The average user throughput of the proposed CC-selection can always achieve better performance than both 'blind' CC-selection and Rel'8 cases. In our proposed CC selection algorithm, power-limited LTE-A UEs are assigned on one CC and therefore will not experience any loss from being scheduled over multiple CCs, while non-power-limited LTE-A UEs not operating close

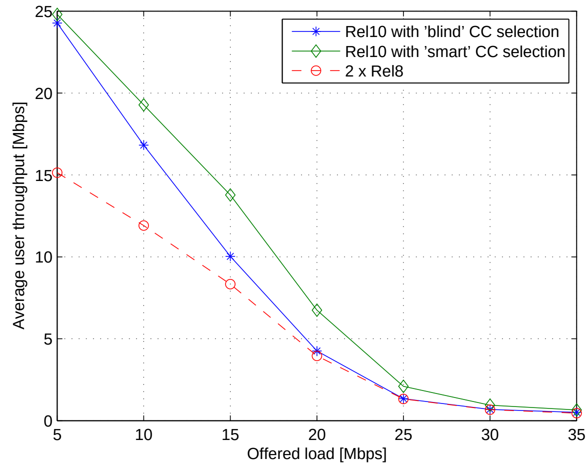

Fig. 5. Average user throughput under different traffic loads in different scenarios, $P_{\text{backoff}} = 4$ dB

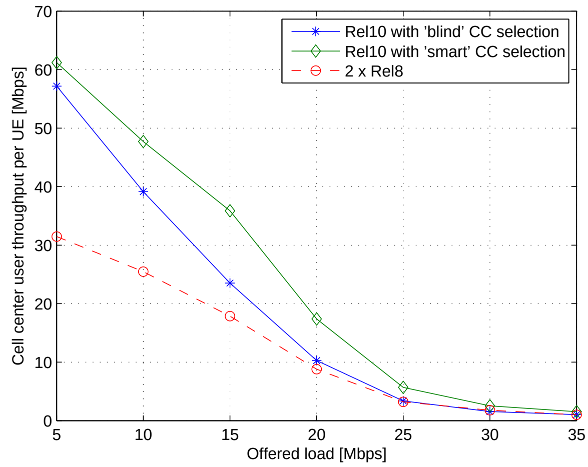

Fig. 6. Cell center user throughput under different traffic loads in different scenarios, $P_{\text{backoff}} = 4$ dB

to their maximum transmission power are assigned on both CCs so that they can benefit from the advantages of carrier aggregation. The average user throughput gain of the proposed algorithm over Rel'8 case is high in low load (64% gain with 5 Mbps offered load), but decreases as the offered load increases (41% gain with 35 Mbps offered load).

Similar phenomenon can be observed for the cell center user throughput shown in Fig. 6. For cell center UEs, the throughput gain over Rel'8 case can be up to 100% in low load, which is much higher than the average user throughput gain. The reason is that for cell center UEs, they usually experience low path loss and the throughput is mainly limited by the transmission bandwidth. Therefore doubling the transmission bandwidth by assigning both CCs to those cell center LTE-A UEs can result in a double of user throughput.

V. Conclusions

In this paper, we have investigated the uplink performance of carrier aggregation in LTE-Advanced systems with different CC selection algorithms. In order to optimize the system performance, we have derived a pathloss threshold that separates the UEs into two categories: power-limited and non-power-limited UEs, and assign only one CC to power-limited LTE-A UEs, but assign multiple CCs to non-power-limited LTE-A UEs. The simulation results verified that our derived pathloss threshold can achieve the optimal performance in terms of cell edge and average user throughput under various traffic loads. By comparing performance between different CC selection algorithms, it is shown that there is a performance loss at cell edge if all LTE-A UEs are assigned on multiple CCs ('blind' CC-selection), due to the limitation of maximum UE transmission power and the additional power back-off needed when transmitting over multiple CCs. On the other hand, assigning LTE-A UEs to one or several CCs depending on their pathloss can achieve the same cell edge performance as Rel'8 case, but shows quite high gains in average and cell center user throughput compared to Rel'8 case. Furthermore, the proposed pathloss-based CC-selection algorithm always exhibits better performance than the 'blind' CC-selection, thus is a good candidate for component carrier selection algorithm in LTE-Advanced systems.

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