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Abstract—In this paper we focus on resource allocation for next generation wireless communication systems with aggregation of multiple Component Carriers (CCs), i.e., how to assign the CCs to each user, and how to multiplex multiple users in each CC. We first investigate two carrier load balancing methods for allocating the CCs to the users- Round Robin (RR) and Mobile Hashing (MH) balancing - by means of a simple theoretical formulation, as well as system level simulations. At Layer-2 we propose a simple cross-CC packet scheduling algorithm that improves the coverage performance and the resource allocation fairness among users, as compared to independent scheduling per CC. The Long Term Evolution (LTE)-Advanced is selected for the case study of a multi-carrier system. In such a system, RR provides better performance than MH balancing, and the proposed simple scheduling algorithm is shown to be effective in providing up to 90% coverage gain with no loss of the overall cell throughput, as compared to independent scheduling per CC.

Index Terms—Multi-carrier, carrier aggregation, load balancing, packet scheduling, LTE-Advanced.

I. INTRODUCTION

INTERNATIONAL Telecommunications Union - Radio Communication Sector (ITU-R) has specified the new concept of International Mobile Telecommunications - Advanced (IMT-Advanced), which targets to achieve a peak data rate of up to 1 Gbps for low mobility and 100 Mbps for high mobility [1]. To fulfill this requirement, the 3rd Generation Partnership Project (3GPP) has started a study item on Long Term Evolution (LTE)-Advanced [2], which supports the transmission over a much wider bandwidth than the LTE systems. At the same time, the IEEE 802.16 group is also evolving the Worldwide Interoperability for Microwave Access (WiMAX) system towards IEEE 802.16m [3], [4]. The bandwidth in both systems can go up to 100 MHz, which is formed by using carrier aggregation of individual Component Carriers (CCs) [2], [4]. As an example, Fig. 1 shows a case when 5 CCs are aggregated together to form a wide bandwidth required for the IMT-Advanced systems.

The structure for a multi-carrier system is illustrated in Fig. 2. The base station first performs admission control, and then employs Layer-3 carrier load balancing to allocate the users
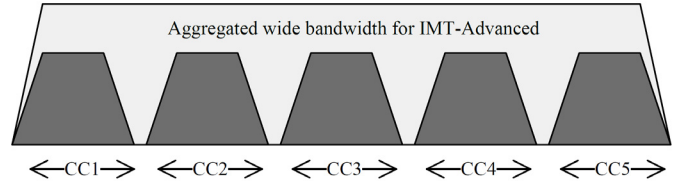
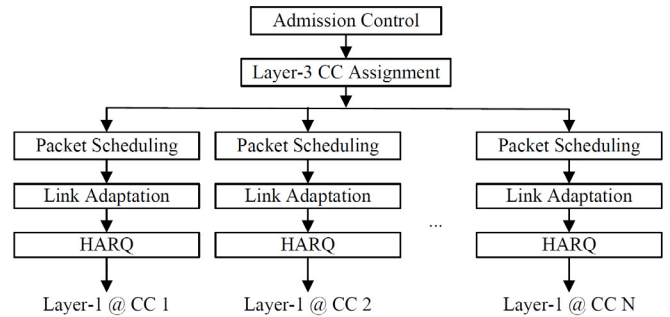Fig. 1. Carrier aggregation of multiple continuous component carriers.

Fig. 2. Structure of a LTE-Advanced system with carrier aggregation.

on different CCs. Different methods for balancing the load across CCs are possible, and will have impact on the system performance [5]. Once the users are assigned onto certain CC(s), Layer-2 Packet Scheduling (PS) is performed. In this context, PS basically refers to the task of assigning time-frequency resources for each of the allocated users on the different CCs. While the independent Layer-1 transmission is assumed, the PS can be performed either independently within each CC (as shown in Fig. 2) or jointly across multiple CCs.

Given the described system setup, we study various Layer-3 carrier load balancing schemes and Layer-2 PS algorithms. The target is to optimize the resource allocation process with the existence of multiple CCs. The study is conducted both in the form of a simple full buffer model with a constant number of users per cell, and a more realistic finite buffer model with Poisson arrival. Note that the full buffer model is chosen because many existing studies are carried out with this mode. It is therefore worthwhile to have a similar case considered here for the purpose of comparison. A simple Layer-2 PS algorithm is proposed, which improves fairness among the users, while at the same time offering attractive overall system performance. Performance is evaluated via both theoretical estimations and system level simulations, with a good match between the two. This gives confidence that the assumed approximations in the theoretical predictions are reasonable, and the theoretical assessment provides further
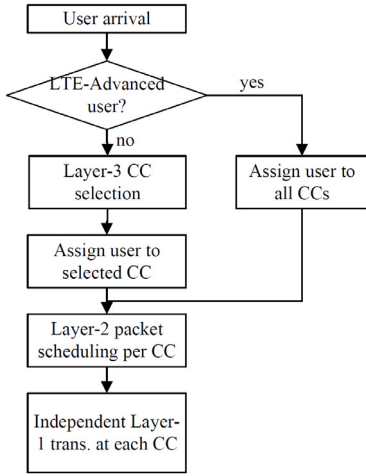
Fig. 3. Different ways to treat the LTE-Advanced users and the LTE-Rel'8 users in a multi-carrier LTE-Advanced system.

insight as compared to pure simulation results.

As a case study, we choose Orthogonal Frequency Division Multiple Access (OFDMA) based LTE-Advanced downlink for the evaluation of different resource allocation techniques. The LTE-Advanced resource allocation process addressed in this paper have similarities with related problems for other systems such as e.g. multi-carrier High Speed Downlink Packet Access (HSDPA) [6], [7] and multi-carrier Code Division Multiple Access (CDMA) [5], [8]–[12]. However, these studies do not consider the case with mixed single-carrier and multi-carrier capable users, which is an expected operation mode for next generation systems. Moreover, only full buffer transmission is considered in [7], and the behavior with finite buffer is suggested as future work. As to the problem of load balancing across CCs, there are many related studies in the literature for CDMA [5], [8]–[12]. However, CDMA systems do not have the same mechanism as in OFDMA for time and frequency domain user multiplexing, so findings from such CDMA systems are not directly applicable for LTE-Advanced. These studies are therefore only used as a starting point for our investigation, where we further modify and enhance those schemes to become applicable for the considered framework with mixed categories of users.

The rest of this paper is organized as follows: Section II outlines the different load balancing and PS techniques under investigation. These techniques are analyzed theoretically in Section IV under both finite and full buffer traffic models, where for finite buffer we use the bursty traffic model presented beforehand in Section III. In Section V, the simulation methodology and assumptions are described. In Section VI and Section VII we compare both the theoretical and system level simulation results for load balancing with different PS algorithms. Finally, Section VIII concludes the paper.

II. RADIO RESOURCE MANAGEMENT

In a multi-carrier LTE-Advanced system, both LTE-Advanced and Rel'8 users may exist at the same time. The LTE-Advanced users can be assigned on all CCs, whereas the Rel'8 users support transmission on only one CC. In order to maximize the radio channel aware multi-user scheduling diversity and improve the trunking efficiency, assume that the LTE-Advanced users are always assigned on all CCs. The base station therefore needs to select a proper CC for each of the Rel'8 users only. Fig. 3 shows how the LTE-Advanced and Rel'8 users are differently treated in a multi-carrier LTE-Advanced system.

With multiple users on each CC, a frequency domain channel aware PS can exploit the frequency and user domain diversity to improve the system performance compared with a channel blind Round Robin (RR) scheduler [13]–[16]. The Radio Resource Management (RRM) framework for a multi-carrier LTE-Advanced system is depicted in Fig. 4, where RRM is placed at the base station. It basically contains two parts: the CC assignment functionality that selects/assigns the CC(s) to each user, and the PS that decides on the resource allocation for the users within each CC. The PS takes the Channel Quality Indicator (CQI) from the feedback link to estimate the achievable throughput (the shaded block) and assigns resources accordingly. The decisions of the RRM are used locally at the base station, as well as sent through the downlink control channel to the users to inform about the allocation. It is worth noting that the load condition and the user past throughput on each CC are available from the base station. Therefore only the CQI is required in the uplink feedback channel. Exchange of the user past throughput on each CC is needed for the cross-CC PS. This is shown in the diagram with the dashed block.

A. Carrier Load Balancing Methods

As mentioned before, the LTE-Advanced users are assigned on all CCs. Two methods for Layer-3 CC load balancing are studied for the LTE-Rel'8 users:

1) RR Balancing:
The RR balancing [8] is also referred to as Combined Carrier Channel Assignment [9], or Least Load [5]. The basic principle is to assign the newly arrived user to the carrier that has the least number of users. Thus, it tries to distribute the load evenly to all carriers. However, there might be small load variations on different CCs as the number of Rel'8 users per cell does not always divide equally on the number of CCs, or because of the random departure of users.

2) Mobile Hashing (MH) Balancing:
The MH balancing method [8], also known as the Independent Carrier Channel Assignment [9] or Random Carrier [5], relies on the output from the terminal's hashing algorithm. The output hash values are uniformly distributed among a finite set, which maps directly on the CC indices [17]. Thereby, it provides balanced load across CCs in the long term. However, at each time-instant, the load across CCs is not guaranteed to be balanced, and as a consequence the system will suffer from reduced trunking efficiency.

B. Layer-2 Packet Scheduling

PS at Layer-2 is performed to assign frequency domain resources to the multiple users. In our study, we select a commonly used scheduler, namely Proportional Fair (PF), following the description as outlined in [16]. PF is aware of
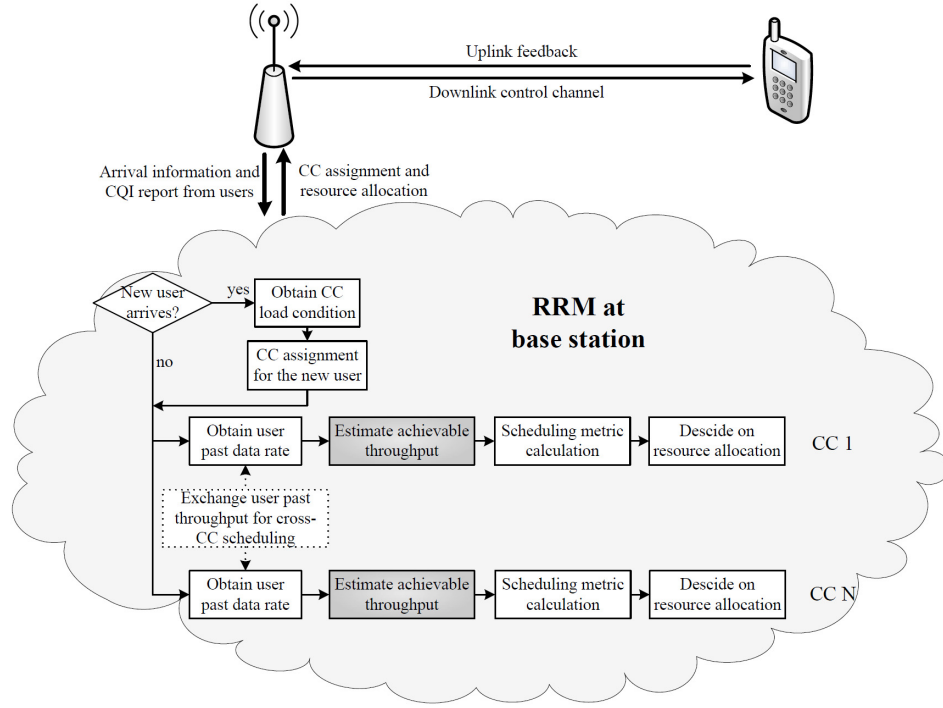
Fig. 4. RRM framework or a multi-carrier LTE-Advanced system. RRM is carried out at the base station, with CQI reporting from users in the uplink. The users are informed of the RRM decisions through downlink control channel.

the frequency selective channel conditions for each user, and thereby offers a Frequency Domain Packet Scheduling (FDPS) gain. With the PF scheduler, the resource is assigned to the user that maximizes the following scheduling metric on each CC [18]:

$$k_{i,j} = \underset{k}{argmax}\{M_{k,i,j}\} \qquad (1)$$

where $k_{i,j}$ is the selected user on the ith CC at the jth Physical Resource Blocks (PRB) group. According to the LTE-Advanced physical layer structure [19], one PRB is the minimum resource element, constituted of 12 consecutive sub-carriers with sub-carrier spacing of 15 kHz, for one transmission time interval. The difference between the independent and the cross-CC PS lies in the way of calculating the scheduling metric for each PRB:

1) Independent PS per CC:
This is the same as the PS in a traditional single carrier system, which does not consider the transmission characteristics on the other CCs. The scheduling metric is calculated by dividing the instantaneous throughput by the average throughput [18]:

$$M_{k,i,j} = \frac{R_{k,i,j}}{\tilde{R}_{k,i}} \qquad (2)$$

$R_{k,i,j}$ is the estimated throughput for user k on the ith CC at the jth PRB group, and $\tilde{R}_{k,i}$ is the average delivered throughput for that user on the same CC in the past. Let us consider two users with the same average channel quality and fast fading statistics, one is LTE-Advanced, and the other is Rel'8. When the load across multiple CCs is balanced, there is the same number of users in each CC. In the long term, the PF scheduler gives an equal share of resources to the users on

the CC assigned to the Rel'8 user [20]. However, the LTE-Advanced user is also scheduled on the other CCs. Therefore it gets overall N times the resources of the Rel'8 user, where N is the number of CCs assigned to the LTE-Advanced user.

2) Cross-CC PS:
By taking the statistics from all CCs into consideration, the PS can achieve an overall better resource allocation than independent PS. In order to reduce the complexity for upgrading the existing LTE systems, we propose a PS algorithm that still operates within each CC. The only difference from independent scheduling per CC is that it takes the past user throughput over all aggregated CCs into account, i.e.

$$M_{k,i,j} = \frac{R_{k,i,j}}{\sum_{i=1}^{N} \tilde{R}_{k,i}} \qquad (3)$$

With (3), the LTE-Advanced users have a reduced scheduling metric because their overall throughput is higher than the throughput per CC. On the other hand, the LTE-Rel'8 users maintain their scheduling metric, because their transmission and reception are restricted to only one CC. They are thereby prioritized as compared with the LTE-Advanced users in resource allocation, which meets the objective of improving fairness among users. The only requirement for upgrading from independent PS is to aggregate the past user throughput across all CCs. Because the throughput within each CC is known at the base station, there is just one extra sum operation for the scheduling in all CCs. No further information exchange or collaboration is needed for the schedulers in different CCs. Thus, it imposes only marginal calculation complexity on top of the independent PS.

III. MODELING OF BURSTY TRAFFIC WITH FINITE BUFFER

The traffic model plays an important role in analyzing the performance of multi-carrier resource allocation techniques. We therefore consider a dynamic traffic model with Poisson arrival and finite buffer size. The arrival, or departure, of users in a network is usually modeled as a birth-death process. The birth-death process is a special case of a continuous-time Markov process, where the states represent the current number of active users, and the transitions are between neighboring states. The 'birth' is the transition towards increasing the active number of users by 1, and a 'death' is the transition towards decreasing the number of active users by 1 [21]. This is a standard $M/M/S/A$ process [22], where the arrival of users follows the Poisson distribution, and the service time follows a negative exponential distribution (M for Markov). S is the state of the system, defined in our case by the number of active users, and A is the corresponding maximum number of users in the system. Although the negative exponential distribution of service time is usually assumed for voice calls [23], it can also roughly represent the time for users to download a finite buffer due to channel quality variations, when assuming PF alike scheduling. The latter is the case considered here, and the aforementioned assumptions are later verified via simulation results, showing a good match.

We use the following notation for the considered traffic model:

S_k System state with k users being served

λ_k Arrival rate in state k, in users per second

μ_k Service rate in state k; in users per second (the average service time is μ_k^{-1})

A Maximum number of users each cell can serve

The admission control in LTE (-Advanced) is assumed to limit the number of users per cell to maximum A users. This leads to the following arrival rate:

$$\lambda_k = \begin{cases} \lambda, & 0 \leq k < A \\ 0, & k \geq A \end{cases} \tag{4}$$

The probability of the system being at state S_k is given by [8]:

$$P_k = \begin{cases} P_0 \displaystyle\prod_{i=0}^{k-1} \frac{\lambda_i}{\mu_{i+1}}, & 1 \leq k \leq A \\ 0, & k > A \end{cases} \tag{5}$$

where P_0 is the probability for being in state S_0, and

$$\sum_{k=0}^{A} P_k = 1 \tag{6}$$

Inserting (5) into (6), we obtain

$$P_0 = \left(1 + \sum_{k=1}^{A} \prod_{i=1}^{k} (\lambda_i/\mu_{i+1}) \right)^{-1} \tag{7}$$

With the probability of each state derived above, we note that if the arrival rate is larger than what the cell can accommodate, some users cannot get enough resources and they will remain in the system; in this case, the number of users will increase over time to A, and thereafter remain at that level.

IV. THEORETICAL ANALYSIS WITH DIFFERENT TRAFFIC MODELS

In this section, the theoretical estimation for an LTE-Advanced system serving a mixture of LTE-Advanced and Rel'8 users is given. The analysis is carried out for both a simple full buffer model and the finite buffer model with bursty Poisson arrival as outlined in Section III. In order to decouple the transmission over multiple CCs, we use the simple approach of independent PS per CC. The performance with cross-CC PS will later be evaluated based on extensive system level simulations.

In an OFDMA system, the FDPS gain from frequency domain PF over RR scheduling generally follows a logarithmic function versus the active number of users [16]. The actual relation depends on the available transmission bandwidth, the scheduling frequency resolution, the channel conditions, and the distribution of users within each cell. For our modeling purposes, we represent the FDPS gain in average cell throughput for an LTE system in [16] with the simple approximation:

$$G_k = \begin{cases} 1, & k = 1 \\ 0.11 * ln(k) + 1.10, & 1 < k \leq 13 \\ 1.38, & k > 13 \end{cases} \tag{8}$$

where k is the number of users for the CC. The relation is valid for a uniform distribution of users over the cell area. It should be noted, however, that the CC selection has no mechanism to guarantee exactly such behavior, as it works independent of user location. We will apply the approximation per CC under the assumption that over a sufficient number of realizations the users on a particular CC will have uniform distribution over the cell area.

A. Full Buffer Transmission with Independent Packet Scheduling per CC

Let us consider a general case with N aggregated CCs and K active users per cell. If we assume that each user has probability α of being an LTE-Advanced user, then the probability of having K_α LTE-Advanced users out of the K active users equals

$$P_{K_\alpha} = \binom{K}{K_\alpha} \alpha^{K_\alpha} (1-\alpha)^{K-K_\alpha} \tag{9}$$

1) Analysis for RR Balancing with Full Buffer Transmission:
If the RR carrier balancing method is used, the average number of users on each CC equals

$$\tilde{K} = K_\alpha + (K - K_\alpha)/N \tag{10}$$

The average cell throughput with K_α LTE-Advanced users is

$$R_{cell,RR}(K_\alpha) = C G_{\tilde{K}}/G_\infty \tag{11}$$

where C is the equivalent cell throughput, but with full buffer transmission and PF scheduler in all CCs. By combining (9), (10) and (11), we get:

$$\tilde{R}_{cell,RR} = \frac{C}{G_\infty} \sum_{K_\alpha=0}^{K} P_{K_\alpha} G_{\tilde{K}} \tag{12}$$

The average user throughput on each CC is the corresponding per CC cell throughput divided by the average number of users. Because the LTE-Advanced users are scheduled on N CCs, their throughput is expected to be N times that of the LTE-Rel'8 users. As a result, we obtain the following expression for the average user throughput

$$\tilde{R}_{user,RR} = N^I \frac{\tilde{R}_{cell,RR}}{\sum\limits_{K_\alpha=0}^{K} P_{K_\alpha} \tilde{K}} = \frac{N^I}{K} \frac{\tilde{R}_{cell,RR}}{\alpha + (1-\alpha)/N} \quad (13)$$

In (13), $I = 0$ if the user is LTE-Advanced, and $I = -1$ for Rel'8 users.

2) Analysis for MH Balancing with Full Buffer Transmission:
If MH is used for carrier load balancing, each LTE-Rel'8 user has equal probability of being assigned any of the CCs, with probability $1/N$. It offers balanced load in the long term and the cell throughput is N times the performance with only one CC. With K_α LTE-Advanced users, the probability for one CC to have k LTE-Rel'8 users is

$$P_k = \binom{K - K_\alpha}{k} \left(\frac{1}{N}\right)^k \left(\frac{N-1}{N}\right)^{K-K_\alpha-k} \quad (14)$$

The cell throughput with K_α LTE-Advanced users is

$$R_{cell,MH}(K_\alpha) = \frac{C}{G_\infty} \sum_{k=0}^{K-K_\alpha} P_k G_{K_\alpha+k} \quad (15)$$

and therefore the overall cell throughput equals

$$\tilde{R}_{cell,MH} = \frac{C}{G_\infty} \sum_{K_\alpha=0}^{K} P_{K_\alpha} \sum_{k=0}^{K-K_\alpha} P_k G_{K_\alpha+k} \quad (16)$$

Although the average user throughput on each CC can be estimated using a similar form as with RR, the overall user throughput is dependent on the load condition on all CCs. Due to this correlation, it is non-trivial to formulate the average user throughput, and we will instead evaluate its performance based on extensive system level simulations.

For the reference RR packet scheduler, the maximum cell capacity is C/G_∞. For both (12) and (16), if $G_k = 1$ for all k (other than 0), we obtain the performance with the frequency domain channel blind RR packet scheduler.

B. Finite Buffer Transmission with Independent Packet Scheduling per CC

Having done the analysis for full buffer transmission, let us now look into the problem of carrier load balancing with finite buffer transmission and Poisson arrival. The bursty traffic model developed in Section III is used for the estimation.

1) Analysis for RR Balancing with Finite Buffer Transmission:
As with full buffer transmission, we assume that each user has probability α of being LTE-Advanced. Since the average channel quality and bandwidth is assumed to be the same for all CCs in our study, they are expected to have the same average performance. We therefore focus on the performance in one CC, and then multiply it by a factor of N to get the overall cell throughput and the LTE-Advanced user throughput. The

LTE-Rel'8 users are scheduled within only one CC, so their throughput equals the per CC user throughput.

With the existence of multiple CCs, the arrival of an LTE-Advanced user will be seen on all CCs, whereas the arrival of an LTE-Rel'8 user has only $1/N$ probability of being scheduled on one CC. This results in an overall arrival rate per CC of

$$\lambda_k(RR) = \begin{cases} \lambda\left(\alpha + \dfrac{1-\alpha}{N}\right), & 0 \le k < A' \\ 0, & k \ge A' \end{cases} \quad (17)$$

where $A' = A\left(\alpha + \frac{1-\alpha}{N}\right)$ is the average admission control limitation on each CC.

From (8), we can estimate the achievable throughput with k users on each CC. The service rate, which is the average number of users who finish their transmissions in a cell during one second, can then be expressed using the throughput and the buffer size,

$$\mu_k(RR) = \begin{cases} \dfrac{C' \, G_k}{F \, G_\infty}\left(\alpha + \dfrac{1-\alpha}{N}\right), & 0 \le k < A' \\ 0, & k \ge A' \end{cases} \quad (18)$$

where C' is the equivalent cell throughput as C, but with finite buffer transmission; F is the fixed buffer size for the user packet transmission, in Mbits.

Inserting (17) and (18) into (5), we get the probability for the system being in state S_k (k users served on each CC) as

$$P_k = \begin{cases} P_0 \prod\limits_{i=0}^{k-1} \dfrac{\lambda_i}{\mu_{i+1}} = P_0(\lambda F/C')^k \prod\limits_{i=1}^{k} G_\infty/G_i, & 1 \le k \le A' \\ 0, & k > A' \end{cases} \quad (19)$$

The average user throughput is

$$\tilde{R}_{user,RR} = N^I \frac{\sum\limits_{k=1}^{A'} P_k \dfrac{C'}{k} \dfrac{G_k}{G_\infty}}{1 - P_0} \quad (20)$$

where $I = 0$ if the user is LTE-Advanced, and $I = -1$ for Rel'8 users. The average cell throughput is equal to the offered load as long as it stays below the threshold C', which is the throughput when a cell is fully loaded, hence:

$$\tilde{R}_{cell,RR} = min\{C', \lambda F\} \quad (21)$$

2) Analysis for MH balancing with finite buffer transmission:
With MH, if some CCs are heavily loaded, one CC with low load may refuse to accept new arrivals because of the maximum user number limit. Thereby the user arrival is not independent across the CCs. The departure of LTE-Advanced users, who are transmitting over unbalanced CCs, cannot be modeled simply within each CC either. Due to the difficulty in modeling the correlated user arrival and departure, we rely solely on simulations to quantify the performance for the MH method.

V. SIMULATION METHODOLOGY AND ASSUMPTIONS

The performance of the algorithms is evaluated in a quasi static downlink multi-cell system level simulator that follows

TABLE I
SYSTEM SIMULATION SETTINGS

Parameter	Setting / description
Test scenario	3GPP Macro-cell case #1 (19 sites, 3 cells per site)
Carrier aggregation pattern	4 CCs at 2.0 GHz frequency, with 10 MHz per CC
Number of PRBs per CC	50 (12 subcarriers per PRB)
Sub-frame duration	1 ms (11 OFDM data symbols plus 3 control symbols)
Modulation and coding schemes	QPSK (1/5, 1/4, 1/3, 2/5, 1/2, 3/5, 2/3, 3/4), 16-QAM (2/5, 9/20, 1/2, 11/20, 3/5, 2/3, 3/4, 4/5, 5/6), 64-QAM (3/5, 5/8, 2/3, 17/24, 3/4, 4/5, 5/6, 7/8, 9/10)
User receiver	2-Rx Interference Rejection Combining
HARQ modeling	Ideal chase combining with maximum 4 retransmissions
Feedback delay	6 ms
CQI reporting	1 CQI per 3 PRBs; 1.6 dB quantization step; log normal error with 1 dB standard deviation
Layer-2 PS	Round Robin in time domain, Proportional Fair in frequency domain
1st transmission Block Error Rate (BLER) target	10%
Traffic type	Full buffer (with 10 users) and finite buffer (Poisson arrival with fixed buffer size of 2 Mbits)
Admission control constraint	Maximum 50 users per cell

the LTE specifications defined in [24], including detailed implementations of Layer-3 CC selection, Layer-2 PS, Hybrid Automatic Repeat Request (HARQ) and Link Adaptation (LA) functionalities. The simulation scenario is Macro-cell case #1 as defined in [25]. The simulation parameters are summarized in Table I. The link to system mapping is based on the exponential effective metric model [26]. The simulation process with the full buffer traffic is conducted as a series of simulation runs (5.0 seconds in each run) with a constant number of 10 users per cell. Multiple simulation runs are required for this traffic model in order to get sufficient statistics, since the traffic model is static in the sense that the 10 users per cell are active all the time. On the other hand, for the finite buffer model with dynamic birth-death, only one long simulation run (with duration of 120 seconds) is needed. The latter is the case because users are created and terminated dynamically during the simulation. Among the 19 macro-sites, only the center-site is simulated. The surrounding sites are used to generate time continuous interference across the full bandwidth.

The following measures are used in our study as performance indicators:

- Average cell throughput: the summation of the user throughput in each cell, averaged across multiple runs (full buffer model), or a single long duration simulation run (finite buffer model).
- Average LTE-Advanced (or Rel'8) user throughput: Average throughput over all the simulated LTE-Advanced (or Rel'8) users.
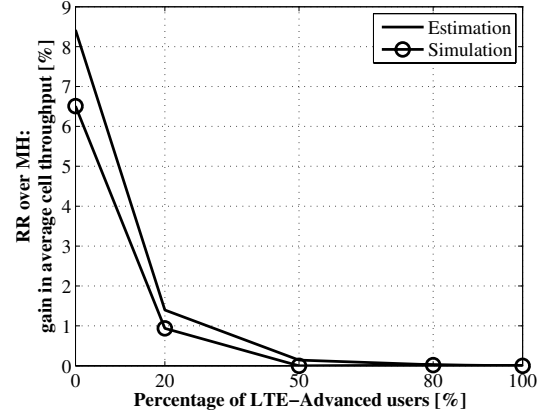- Coverage: The 5th percentile worst user throughput over all simulated users.

Fig. 5. Gain in average cell throughput by using RR balancing as compared to MH. Performance is evaluated with 10 users per cell and different ratios of LTE-Advanced users. Both estimated and simulated results are shown.
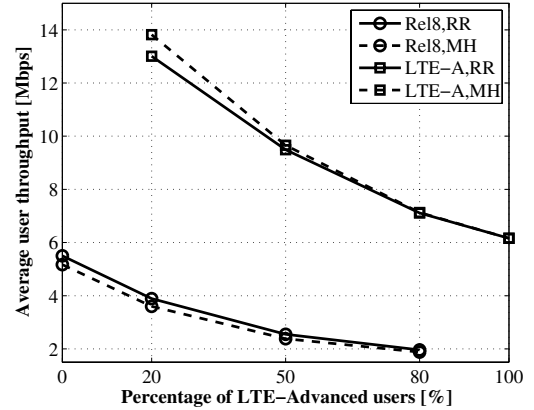

Fig. 6. Average user throughput for the two carrier load balancing methods. Results are obtained via simulation with 10 users per cell and different ratios of LTE-Advanced users.

VI. RESULTS WITH INDEPENDENT SCHEDULING PER COMPONENT CARRIER

In this section, we provide the system performance based on the theoretical model. The accuracy of the derived expressions is verified via comparison against simulation results.

A. Full Buffer Performance with Independent Packet Scheduling per CC

The relative gain in average cell throughput by using RR over MH is shown in Fig. 5, with different ratios of LTE-Advanced users. Both theoretical estimations and simulation results are shown. The absolute values of average user throughput are summarized in Fig. 6. In order to have a clear view of the performance for different user categories, the throughput is plotted for both LTE-Advanced and Rel'8 users. This is different from the cell throughput, which is aggregated over all categories of users, and therefore is plotted with only one curve. From these two figures, we extract the following observations:

1) In terms of average cell throughput, there is a good match between the theoretical estimates and the system-level simulations, with maximum 1% deviation between

the two. When all users are Rel'8, RR balancing provides ~7% higher cell throughput compared to MH. However, the gain decreases fast with the ratio of LTE-Advanced users and it vanishes for more than 20% of LTE-Advanced users. The reason is that the assignment of CCs to the LTE-Advanced users is always balanced, and a higher ratio of LTE-Advanced users thereby improves the overall balancing.

2) With the co-existence of both LTE-Advanced and Rel'8 users, the Rel'8 users achieve much lower throughput than the LTE-Advanced users. Because the coverage throughput is taken as the 5% worst user throughput, a low Rel'8 user throughput therefore indicates poor coverage performance.

3) When all users are LTE-Rel'8 (the ratio of LTE-Advanced users is 0%), the user throughput (and also the average cell throughput) is lower compared to the case when all users are LTE-Advanced (with ratio 100%). This is in coherence with the previous analysis, in that both the trunking efficiency and multi-user gain increases with the ratio of LTE-Advanced users.

4) RR provides a higher throughput for the LTE-Rel'8 users, but lower throughput for the LTE-Advanced users, as compared to MH. This is because RR distributes the Rel'8 users evenly on all CCs, therefore they can get more resources than with MH balancing, and hence higher throughput. At the same time, the throughput for LTE-Advanced users is reduced, as fewer resources are left for them. However, looking at the two most important performance indicators, average cell throughput and coverage throughput, RR is always better than MH.

It is also worth noting that all resources are utilized when there is at least one user per CC. There will be unused resources only when some CCs are empty (e.g. due to a low number of users and high ratio of LTE-Rel'8 users). With the given system configuration, there is a sufficient number of users and hence the resources are fully utilized.

B. Finite Buffer Performance with Independent Packet Scheduling per CC

With finite buffer transmission, the performance depends strongly on the buffer size and the arrival rate. In this study, we use a fixed buffer size of 2 Mbits and vary the arrival rates to obtain different load conditions. The evaluation is done assuming that 50% of the users are LTE-Advanced. From simulations, we know that for these conditions the maximum achievable cell throughput in a fully loaded LTE-Advanced system is on the order of 49 Mbps. Taking this value as input for the bursty traffic model ($C' = 49$ Mbps in (20)), we estimate performance based on the simple model.

The resulting theoretical and simulated performance for average user throughput is shown in Fig. 7. From this figure we can see that the simple model is able to provide a good estimation. Although not presented here, we have found that the average cell throughput also matches exactly the estimation given by (21). As with full buffer traffic model, the Rel'8 user throughput is much below the LTE-Advanced user throughput.
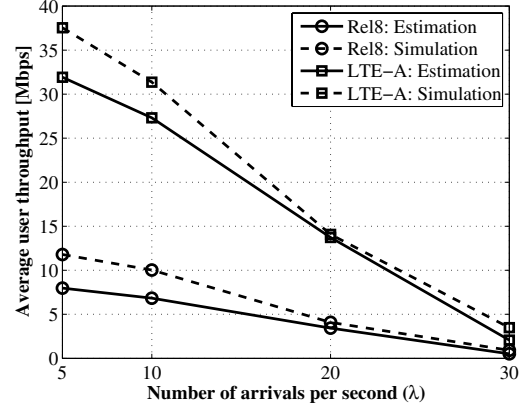

Fig. 7. Average user throughput with 50% of LTE-Advanced users and different user arrival rates. Buffer size is 2 Mbits, load balancing is RR.
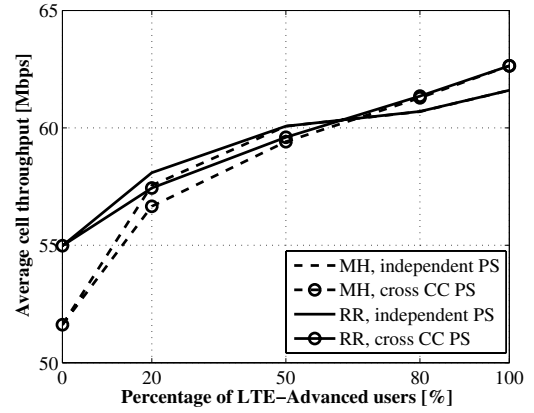

Fig. 8. Average cell throughput for independent or cross-CC PS with different carrier load balancing methods. The full buffer traffic model is assumed.

VII. RESULTS WITH DIFFERENT PACKET SCHEDULING ALGORITHMS

In Section VI, we have seen that the load balancing method of RR offers better performance than MH. However, the Rel'8 users suffer from much lower performance than LTE-Advanced users, which will cause degraded coverage. By using the cross-CC PS as introduced in Section II, we can increase the scheduling priority for the Rel'8 users and offer better coverage than with independent PS per CC.

A. Full buffer performance with independent or cross-CC packet scheduling

The performance with full buffer transmission is shown in Fig. 8 and Fig. 9 for the performance in average cell throughput and coverage, respectively. The performance for MH is also presented, which is always worse than RR with the same Layer-2 PS.

From Fig. 8 we can see that there is no obvious gain, or loss, in cell throughput by using cross-CC PS over independent PS. However, in terms of coverage performance, Fig. 9 shows that cross-CC PS has a significant improvement over independent PS. When LTE-Rel'8 users are mixed together with the LTE-Advanced users, with RR balancing the gain is 50% (when
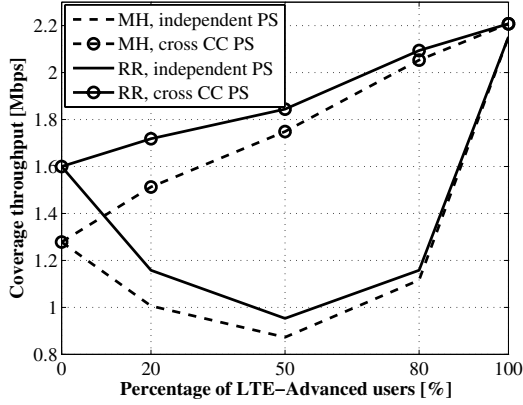
Fig. 9. Coverage performance for independent or cross-CC PS with different carrier load balancing methods. The full buffer traffic model is assumed.
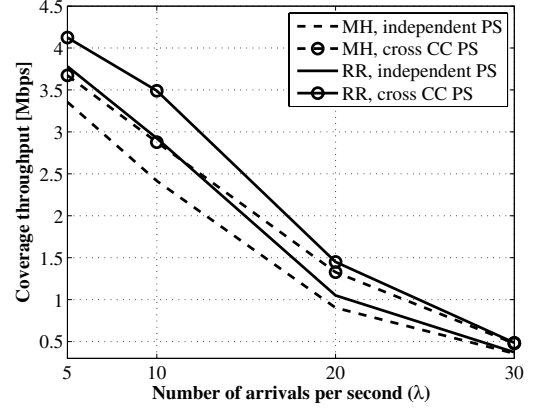

Fig. 10. Coverage performance for independent or cross-CC PS with different carrier load balancing methods. Mixed user scenario with 50% LTE-Advanced users. Different arrival rates are investigated.

20% of the users are LTE-Advanced) to 90% (when 50% of the users are LTE-Advanced) over independent PS. This clearly shows the importance of using cross-CC PS for achieving acceptable cell-edge user throughput (coverage). It is also observed that when all users are LTE-Advanced, there is no difference between the RR and MH balancing method, because each user is assigned on all CCs; when all users are Rel'8, cross-CC PS offers the same performance as independent CC, as each user is assigned on only one CC.

The reason for the poor performance of independent PS as compared with cross-CC PS can be explained as follows: With independent PS, if the ratio of LTE-advanced users is low, the coverage throughput is collected from the LTE-Rel'8 users, because they have overall much worse performance than the LTE-Advanced users. From (13) we can see, as the ratio of LTE-Advanced users increases, the Rel'8 users will get less and less resources, and their throughput will decrease (see also Fig. 6). As a consequence, the coverage performance is also reduced. When the ratio of LTE-Advanced users is high, many LTE-Advanced users with poor channel quality will have worse performance than the Rel'8 users who experience good channel conditions. This helps to improve the worst user performance. As an extreme case, when all users are LTE-Advanced, the coverage throughput should be much higher than when all are Rel'8. Due to these reasons, the coverage throughput with independent scheduling will first decrease, then increase with the ratio of LTE-Advanced users. Cross-CC PS does not suffer from this behavior, because the scheduling is performed as a function of the past average delivered throughput on all CCs, and the fairness between LTE-Advanced and Rel'8 users is better maintained than with independent PS.

B. Finite buffer performance with independent or cross-CC packet scheduling

For finite buffer traffic model, we only look into the coverage performance, as the average cell throughput is hardly affected by the different PS algorithms. Two cases are considered, the first case with 50% of the users being LTE-Advanced, and different arrival rates. The second case assumes an average load of 20 user arrivals per second per cell, but with different
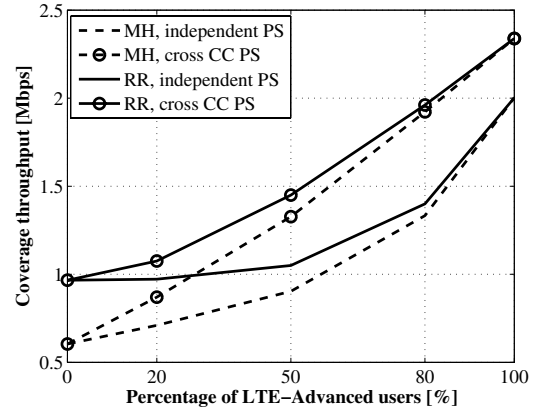

Fig. 11. Coverage performance for independent or cross-CC PS with different carrier load balancing methods. Cell load is medium with 20 user arrivals per second within each cell. Mixed user scenario with a variable ratio of LTE-Advanced users.

ratios of LTE-Advanced users. The results are summarized in Fig. 10 and Fig. 11, respectively.

From Fig. 10 we can see that the coverage decreases with arrival rate. The reason is that as cell load increases, the total transmission resource is shared among an increasing number of users. Fig. 11 shows that when the cell load is fixed, a higher ratio of LTE-Advanced users gives a corresponding improvement in coverage. The reason is that with finite buffer transmission, LTE-Advanced users can finish their data transmission faster than Rel'8 users; as the ratio of LTE-Advanced users increases, a larger number of users are served in a short time, leaving more resources for the remaining users and a better coverage performance.

In both Fig. 10 and Fig. 11, we can confirm that RR offers a better performance than MH, which is aligned with similar studies of RR and MH carrier load balancing for multi-carrier CDMA systems [9]. Secondly, cross-CC PS offers a gain over independent PS ranging between 10% and 40%. The exact gain depends on the system configurations, e.g. traffic model and the LTE-Advanced user ratio.

For both full and finite buffer traffic models, cross-CC PS hardly affects the average cell throughput. Meanwhile, it

significantly improves the coverage performance. This means the throughput gap between the two categories of users is reduced, and therefore the fairness is improved. This benefit of cross-CC PS is achieved by de-prioritizing the users that are assigned with multiple CCs, as shown in (3).

VIII. Conclusion

In this paper, we have studied the problem of how to optimize the resource allocation process in a multi-carrier system, while maintaining low complexity. The LTE-Advanced system is selected as a case study. We first focus on different Layer-3 carrier load balancing methods, which assign the CCs to each user. Both simple theoretical and simulation results are obtained, which show that with low number of users and low percentage of LTE-Advanced users, the load balancing method of RR achieves better performance than the MH balancing.

After the assignment of CCs, we look into the scheduling of resources in Layer-2. Using independent PS per CC is found to suffer from poor coverage performance. We therefore propose a cross-CC PS algorithm, which is a simple extension of the existing PF scheduler. The cross-CC algorithm improves the scheduling priority for the Rel'8 users on their serving CCs. As a result, it is able to significantly improve the system fairness and coverage. In an LTE-Advanced system, the gain in coverage over independent PS is up to 90% with full buffer transmission and 40% with finite buffer transmission, depending on the ratio of LTE-Advanced users. Despite the high gain in coverage, it gives no degradation in the average cell throughput, and therefore is an attractive candidate for the layer-2 PS.

Acknowledgment

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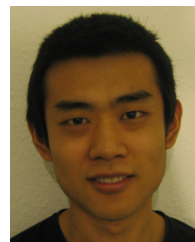
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