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Abstract Radio Resource Management Framework for System Level Simulations in LTE-A Systems

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Abstract—This paper provides a simple mathematical model of different packet scheduling policies in Long Term Evolution-Advanced (LTE-A) systems, by investigating the performance of Proportional Fair (PF) and the generalized cross-Component Carrier scheduler from a theoretical perspective. For that purpose, an abstract Radio Resource Management (RRM) framework has been developed and tested for different ratios of users with Carrier Aggregation (CA) capabilities. The conducted system level simulations confirm that the proposed model can satisfactorily capture the main properties of the aforementioned scheduling metrics without any need for explicit design at a subframe resolution; hence, making it a promising candidate for a convenient scheduler implementation in simulators with simplified RRM modelling.

Index Terms—LTE-A; Radio Resource Management (RRM); Carrier Aggregation; Modeling; Packet Scheduling

I. INTRODUCTION

To meet the growing demand for higher data rates, Carrier Aggregation (CA) is introduced in Release 10 Long Term Evolution-Advanced (LTE-A) specifications. In CA mode, two or more Component Carriers (CC) are aggregated to support effectively wider transmission bandwidths [1], reaching up to 100 MHz. Fig. 1 illustrates the basic LTE-A architecture, where the set of parallel streams represents the number of available CCs deployed at the base station. Being designed to be backwards compatible with Release 8 User Equipments (UE), which do not have CA capabilities, each CC follows the principles of the LTE Radio Resource Management (RRM) framework. Users are assigned onto one or more CCs depending on terminal capabilities and resource allocation takes place via dynamic packet scheduling, either independently or jointly among different CCs. Link adaptation and Hybrid Automatic Repeat Request (HARQ) management for transport block transmissions are solely performed at a CC independent basis.

The requirements of simulation tools heavily depend on the case study. Dynamic packet scheduling investigations [2-4] are typically performed with quasi static system level simulators, where the aforementioned framework is explicitly modelled. Scheduling decisions are taken at a millisecond basis; however, at the cost of large simulation runtime. For studies, where some of these system components are not so relevant for performance evaluation, but the simulations still need to be

conducted in a LTE-A environment, the detailed design of all L1/L2 aspects would be exhaustive. E.g. investigations related to Self-Organizing Networks (SON) require a lighter approach in terms of modelling the LTE-A RRM functionalities, since long simulations are needed for convergence to be achieved.

For that purpose, this paper contributes a simple mathematical LTE-A RRM framework that realistically emulates the performance of 2 particular scheduling policies, also referred to as independent Proportional Fair (PF) per CC and generalized cross-CC PF [2], without requiring an explicit subframe-based implementation. In particular, a set of fairness scaling factors is utilized for modifying the resource allocation decisions subject to the UE assignment onto the different CCs and the desired RRM policy to be applied. However, since no additional Signal-to-Noise plus Interference (SINR) considerations are included, it is valid for interference limited scenarios, where the SINR distributions over the deployed CCs are similar and system performance depends only on how users are assigned onto the available CCs.

The remainder of the paper is structured as follows. Section II provides a brief overview of packet scheduling in LTE-A systems, while the proposed abstract RRM framework is presented in Section III. The simulation assumptions along with the corresponding results are available in Section IV and V respectively. Finally, section VI concludes the paper.

II. DYNAMIC PACKET SCHEDULING IN LTE-A

This section outlines the basic properties of different packet scheduling policies in LTE-A systems. More specifically, we

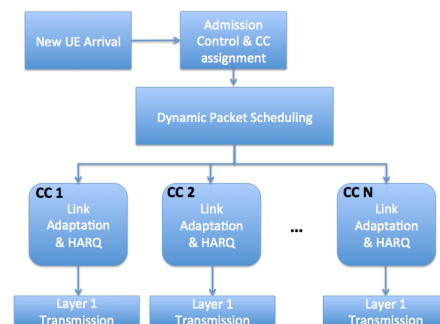


Fig. 1. Basic LTE-A Architecture

focus on the CC independent PF scheduler and the joint cross-CC scheduling approach.

A. Independent Proportional Fair per CC

The PF metric is a well-known example of packet scheduling that maximizes network utility (defined as the sum of logarithmic user throughput) by exploiting multi-user diversity [5]. In the long term, user fairness is guaranteed and resources are equally shared among UEs regardless of channel conditions and fading characteristics [6]. For CA systems and independent PF scheduling per CC, the j^{th} Physical Resource Block (PRB) on carrier i will be assigned to the user $u_{i,j}$ according to:

$$u_{i,j} = \arg \max_u \left\{ \frac{R_{u,i,j}}{\tilde{R}_{u,i}} \right\} \quad (1)$$

where $R_{u,i,j}$ is the instantaneous throughput of user u at the j^{th} PRB of CC i and $\tilde{R}_{u,i}$ is the past user perceived throughput on the same CC averaged over a specific time window. However, since non-CA users have limited access to the overall available spectrum, maximizing the network utility within the CC does not necessarily imply that the global utility over all CCs is maximized.

In fact, CA UEs will be significantly favored if PF scheduling is performed independently per CC, while non-CA users co-exist in the system. Let us consider a scenario with n CCs and equal split of non-CA and CA UEs in the macrocell area. Assuming a load balancing mechanism that distributes evenly the non-CA users over the different CCs, then the total amount of PRBs allocated per CA terminal will be n times larger than the resource share of the non-CA UEs. Obviously, this behavior may not be desired by the operator as it will starve out legacy non-CA devices.

B. Cross-CC Packet Scheduling

The joint cross-CC scheduling [3] overcomes the aforementioned resource allocation fairness problem in LTE-A systems by modifying the PF metric as follows:

$$u_{i,j} = \arg \max_u \left\{ \frac{R_{u,i,j}}{\sum_{i=1}^n \tilde{R}_{u,i}} \right\} \quad (2)$$

By considering in (2) the aggregated past experienced user throughput over all CCs, the scheduling priority for CA UEs actually decreases. Hence, resource starvation for non-CA devices is avoided and significant cell edge throughput gains can be derived without any noticeable impact on the average cell throughput [3]. In principle, cross-CC scheduling maximizes the global network utility in LTE-A systems with different mixtures of non-CA and CA users, as shown in [2]. Nevertheless, a more flexible resource allocation is feasible by generalizing (2) as follows:

$$u_{i,j} = \arg \max_u \left\{ \frac{\alpha \cdot R_{u,i,j}}{(\sum_{i=1}^n \tilde{R}_{u,i})^\beta} \right\}, \quad (3)$$

where the a (*user type specific*) and b weighting parameters are utilized for adjusting the UE category fairness. E.g. by setting $a = 1$ for CA UEs and $a > 1$ for non-CA devices, the

scheduling priority of non-CA devices will further improve, and vice versa. Nevertheless, any other combination rather than $\alpha = \beta = 1$ results in utility loss.

III. ABSTRACT LTE-A RRM FRAMEWORK

In this section, the proposed abstract LTE-A RRM model is thoroughly described. A set of fairness scaling factors is introduced and, depending on the emulated scheduling metric, the corresponding long term resource shares can be approximated without any need for exact implementation at a subframe basis.

A. Problem Formulation

Let us consider a LTE-A scenario with n CCs per macrocell area. Let N_i and N_{CA} denote the number of non-CA and CA users in the i^{th} CC. Obviously:

$$N_{nonCA} = \sum_{i=1}^n N_i, \quad (4)$$

where N_{nonCA} is the total number of legacy non-CA users in the cell area. Given that K_{tot} is the CC bandwidth, the allocated resource share per UE class, assuming independent PF scheduling per CC, will be:

$$K_i^{nCA} = \frac{K_{tot}}{N_i + N_{CA}} \quad (5)$$

$$K^{CA} = \sum_{i=1}^n \frac{K_{tot}}{N_i + N_{CA}} \quad (6)$$

Since CA UEs are allocated resources in all CCs, we can define the virtual amount of CA terminals in the i^{th} CC, $V_i^{N_{CA}}$, as follows:

$$V_i^{N_{CA}} = w_i N_{CA}, \quad (7)$$

where w_i are the virtual scheduling weights for the CA users on the i^{th} CC. Thus, based on (7), the modified resource shares per UE class can be expressed by:

$$K_i^{nCA} = \frac{K_{tot}}{N_i + w_i N_{CA}} \quad (8)$$

$$K^{CA} = \sum_{i=1}^n \frac{w_i K_{tot}}{N_i + w_i N_{CA}} \quad (9)$$

(8) and (9) indicate that resource allocation decisions could be adjusted by different w_i assignments. Therefore, given that α_u is the target Resource Share Ratio (RSR) between non-CA and CA UEs, the proper virtual scheduling weights need to be found, satisfying:

$$K_1^{nCA} = K_2^{nCA} = \dots = K_n^{nCA} = \alpha_u \cdot K^{CA} \quad (10)$$

subject to:

$$\sum_{i=1}^n w_i = \frac{1}{\alpha_u} \quad (11)$$

$$w_i \in [0, 1/\alpha_u] \quad (12)$$

In such a manner, the fairness adjustments provided by the α , β parameters of the generalized cross-CC scheduler can be emulated by spanning α_u over different RSRs. Note that (11) and (12) are mandatory constraints for guaranteeing that the sum of $V_i^{N_{CA}}$ over all CCs along with the sum of total resources allocated per CC will not exceed N_{CA} and K_{tot} respectively.

B. Solution for virtual scheduling weights

Based on (10), we can express all scheduling weights as a function of w_1 :

$$w_i = w_1 + \frac{N_1 - N_i}{N_{CA}}, i = 2, \dots, n, \quad (13)$$

whereas by combining (4), (11) and (13), the set of virtual scheduling weights can be defined, as follows:

$$w_i = \frac{1}{n \cdot \alpha_u} + \frac{N_{nonCA} - n \cdot N_i}{n \cdot N_{CA}}, i = 1, \dots, n \quad (14)$$

In order to illustrate the behavior of (13), a simple case with 2 deployed CCs, 4 CA terminals and different non-CA UE distributions is assumed for $\alpha_u = 1$. Resource fairness performance between the 2 different user categories is evaluated by the obtained average CA UE RSR, K_u , defined as:

$$K_u = \frac{K^{CA}}{(\sum_{i=1}^n N_i K_i^{nCA}) / N_{nonCA}} \quad (15)$$

Both K_u and the virtual CA weights on the 1st CC ($w_2 = 1 - w_1$) are demonstrated in Fig. 2 and Fig. 3 respectively. We observe that ideal resource share fairness is guaranteed for all different UE assignments, as $1/\alpha_u = K_u = 1$. This model behavior is expected since (13) derives directly from (10). Note that $w_j > w_i$ for $N_i > N_j$; hence, CA UEs are allocated more resources in the CCs where fewer non-CA users are assigned, in order to maintain fairness. However, α_u might not always be feasible, simply due to the UE assignment onto the different CCs. In these cases, the weights solution violate (12), as it is clearly shown by Fig. 3. This limitation is overcome if the negative weights are truncated to zero and the remaining ones are normalized accordingly, such as to fulfill (12):

$$\widetilde{w}_i = \begin{cases} 0 & , \widetilde{w}_i < 0 \\ \frac{1}{n \cdot \alpha_u} + \frac{N_{nonCA} - n \cdot N_i}{n \cdot N_{CA}} & , \widetilde{w}_i \geq 0 \end{cases} \quad (16)$$

$$w_i = \frac{\widetilde{w}_i}{\alpha_u \sum_{i=1}^n \widetilde{w}_i} \quad (17)$$

The results related to solution (16)-(17) are also depicted in Fig. 2 and 3, as the regions of resource fair infeasibility are indicated by $K_u > 1$, while $w_i \in [0, 1]$ for any UE assignment onto the 2 CCs. Obviously, in the $K_u > 1$ regions, CA devices will be scheduled in a single CC.

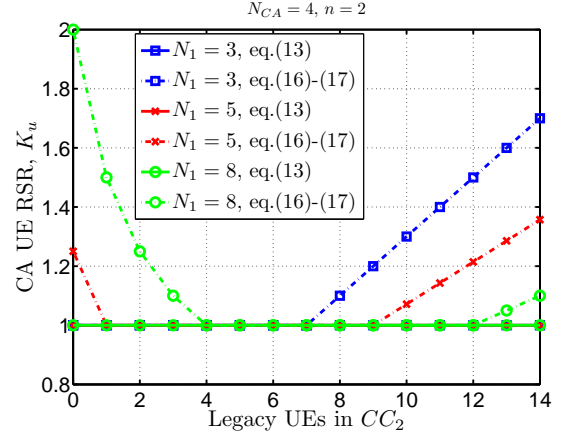


Fig. 2. K_u for different non-CA UE assignments onto the 2 CCs. 4 CA users are assumed and $\alpha_u = 1$.

IV. SIMULATION ASSUMPTIONS

The proposed abstract LTE-A RRM model is implemented in the system level simulator presented in [7][8]. Hence, the simulation tool has been extended accordingly such as to support downlink CA simulations. The performance of the mathematical framework is assessed in the CA deployment scenario 1 [9], consisting of 4 CCs deployed at 2 GHz. Statistics are collected from a sufficiently large number of snapshots for different user positions and several CA UE ratios. Full buffer traffic is simulated and non-CA UEs are assigned onto the different CCs based on the Least Load (LL) algorithm [10]. CA devices are assigned on all CCs. The major simulations assumptions are listed in Table I.

The UE perceived throughput derives directly from SINR-to-throughput mapping curves, calibrated by extensive link level simulations with explicit implementation of all packet scheduling, link adaptation and HARQ procedures. It is always assumed that the optimal Modulation and Coding Scheme (MCS) is applied for each user, depending on its experienced SINR conditions. The impact of the Frequency Domain Packet

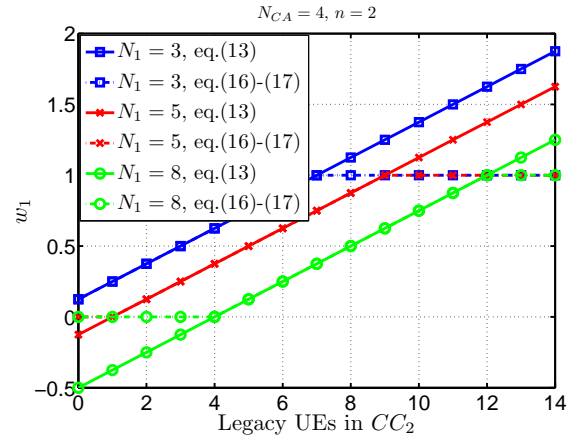


Fig. 3. Cross-CC weights solution for different non-CA UE assignments onto the 2 CCs. 4 CA users are assumed and $\alpha_u = 1$.

TABLE I
SYSTEM SIMULATION PARAMETERS

Parameter	Value
Scenario	CA Scenario 1 (19 sites, 3 cells per site)
Inter-Site Distance	500 m
Pathloss	$128.1 + 37.6 \cdot \log_{10}(R)$
CC Information	4 CCs at 2GHz (10 MHz each)
Resources per CC	50 PRB
Number of UEs per cell	10
CA UE Ratio	0%, 20%, 50%, 80% and 100%
Antenna Configuration	1x2
Transmit Power	43 dBm per CC
Traffic Type	Full Buffer
CA Packet Scheduler	Independent PF versus Cross-CC

Scheduling (FDPS) gain is also included in the system modelling by selecting the proper curve subject to the amount of users that are scheduled in the cell. Therefore, the experienced UE throughput, $r_{u,i}$, of user u on the i^{th} CC is calculated as follows:

$$r_{u,i} = R(\text{SINR}_{u,i}) \cdot f_{u,i}, \quad (18)$$

where $f_{u,i}$ is the number of resources allocated to user u on the i^{th} CC and $\text{SINR}_{u,i}$ the average SINR per PRB. The generalized cross-CC performance is approximated by calculating the scheduling weights according to (16)-(17), while $f_{u,i}$ derives directly from (8) and (9) depending on the user type. Similarly, (5) and (6) are utilized for the case of independent PF scheduling per CC.

The Key Performance Indicators (KPI) for the conducted study are the network utility (sum of logarithmic throughput in Mbps), the 5%-ile user throughput (coverage) and the average cell throughput.

V. SIMULATION RESULTS

A. Impact of target RSR α_u

Fig. 4 illustrates the normalized network utility, coverage and average cell throughput for different α_u settings and 50% CA UE ratio. All related KPIS are normalized by the values associated to $\alpha_u = 1$. Indeed, network utility is maximized for $\alpha_u = 1$, emulating the performance of the generalized cross-CC scheduler with $\alpha = \beta = 1$. This is case when the weights are calculated such as to provide the maximum possible fairness between non-CA and CA users. Consequently, the highest coverage throughput gains are derived as well. Note that for this particular simulation setting, the $\alpha_u = 0.25$ case actually represents the independent PF scheduler per CC. Therefore, no impact on the average cell throughput is observed compared to $\alpha_u = 1$, a fact that is aligned with other related studies in the literature [3]. Any other fairness adjustments performed by α_u replicate different combinations of the α, β parameters of the generalized cross-CC scheduler and consequently the network utility decreases.

The impact of different packet scheduling approaches on the experienced UE throughput per user category is shown in Fig. 5. As expected, CC independent PF scheduling favors significantly CA terminals, achieving n times higher throughput

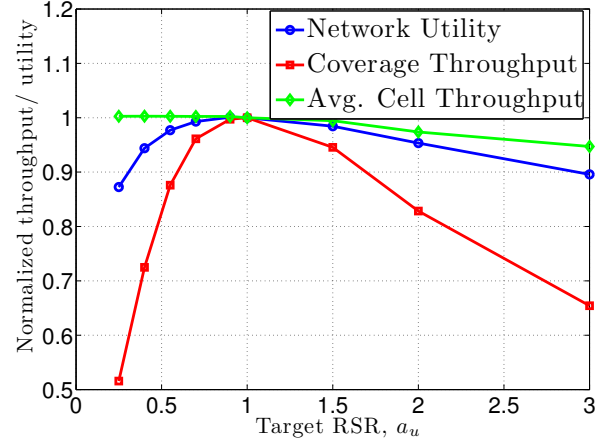


Fig. 4. Normalized network utility, coverage and avg. cell throughput for different target α_u values. 50% of CA UE ratio is assumed.

compared to non-CA UEs. Nevertheless, this performance gap is diminished when the joint scheduling approach is emulated by setting $\alpha_u = 1$.

B. Impact of CA UE Penetration

Since it has been confirmed that the performance of cross-CC scheduling can be emulated by $\alpha_u = 1$, the theoretical approximation is investigated for different ratios of CA devices. The coverage throughput for different CA UE ratios is depicted in Fig. 6. We observe that the cross-CC solution enhances significantly the cell edge throughput, whenever non-CA and CA users co-exist in the network, providing gains that are in the same range with the ones derived in [3]. More specifically, for the cases of 20%, 50% and 80% of CA UE ratio, the recorded coverage gains are 44%, 92% and 78% respectively. Note that for ratios above 50%, the performance of the independent PF improves, since the coverage throughput statistics are also biased by cell edge CA UEs that actually experience higher data rates.

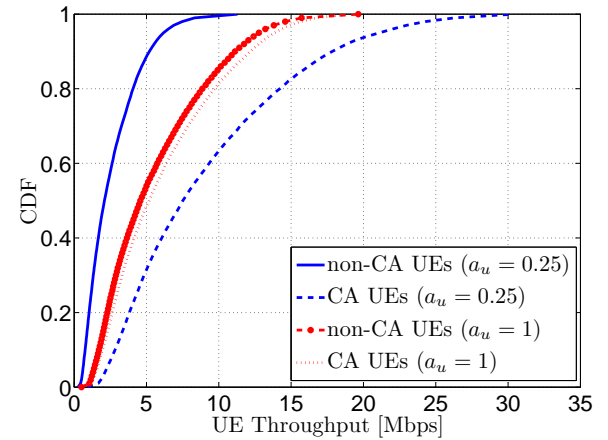


Fig. 5. CDF for non-CA and CA users for different α_u values. 50% of CA UE ratio is assumed.

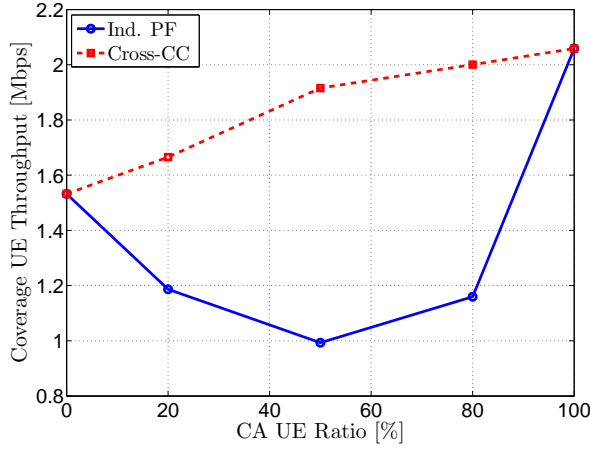


Fig. 6. Coverage throughput for different CA UE ratios

The significant fairness enhancements between the 2 user categories is also highlighted by the network utility, that is provided in Fig. 7. In principle, higher utility is achieved by the cross-CC solution, an observation that is in very good agreement with the simulation results in [2].

Finally, Fig. 8 demonstrates the corresponding average cell throughput results. Once again, the abstract RRM model realistically replicates the subframe implementation, as similar system performance is achieved, regardless of the CA UE penetration and the scheduling approach.

VI. CONCLUSIONS

In this paper, an abstract RRM framework for system level simulations in LTE-A systems has been developed, flexible enough to emulate different packet scheduling policies in scenarios with a mixture of non-CA and CA users. In particular, a set of weighting factors is introduced that adjusts resource allocation decisions depending on the fairness to be maintained between the different UE categories. The model behavior has

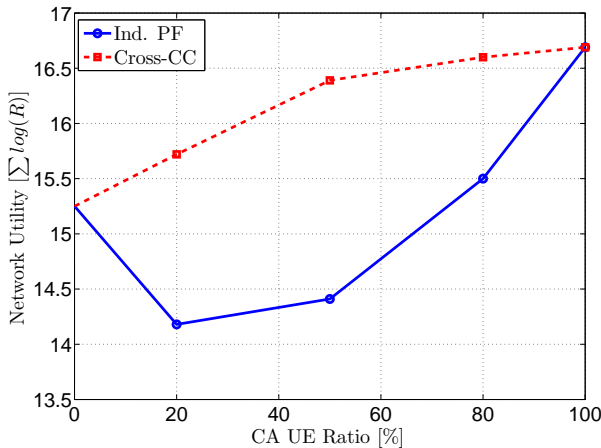


Fig. 7. Network utility for different CA UE ratios

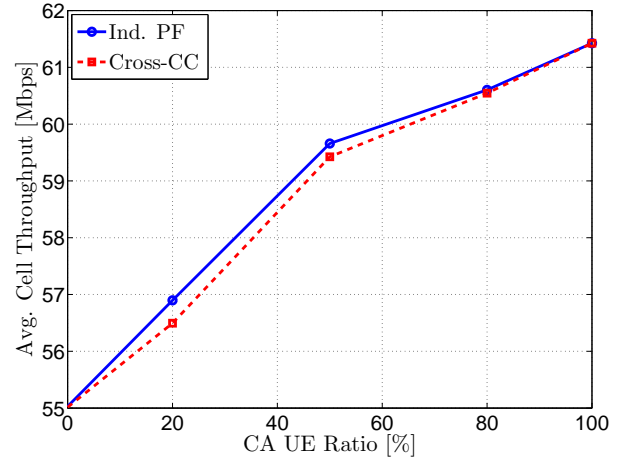


Fig. 8. Average cell throughput for different CA UE ratios

been tested for 2 particular packet scheduling policies, also denoted as CC independent PF and generalized cross-CC scheduler. Results have shown that the performance of the aforementioned metrics can be satisfactorily approximated in an abstract manner, without any requirement for explicit design at a subframe basis. Therefore, it could be considered as an excellent candidate for a scheduler implementation in simplified system level simulators, where the detailed modelling of all L1/L2 LTE-A aspects would have been a rather exhaustive approach.

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