Edge-prioritized Channel- and Traffic-aware Uplink Carrier Aggregation in LTE-Advanced Systems

Rajarajan Sivaraj*, Amit Pande*, Kai Zeng†, Kannan Govindan‡, Prasant Mohapatra*
Department of Computer Science, University of California, Davis, USA*,
Department of Computer and Information Science, University of Michigan, Dearborn, USA†,
Crash Avoidance Metrics Partnership, Michigan, USA‡
{rsivaraj,pande,pmohapatra}@ucdavis.edu*,kzeng@umich.edu†,gkannan16@gmail.com‡

***Abstract*—LTE-Advanced (LTE-A) systems support wider transmission bandwidths and hence, higher data rates for bulk traffic, as a result of Carrier Aggregation (CA). However, existing literature lacks efforts on channel-aware CA, especially in the uplink. The cell-edge users particularly suffer from exhaustion of resources, higher fading losses, lower SINR values (hence, requiring a higher power consumption) due to lossy channels that their traffic requirements are least-satisfied by channel-blind CA. This paper addresses the above concern by proposing an edge-prioritized channel- and traffic-aware uplink CA comprising Component Carrier (CC) assignment and resource scheduling. The LTE-A UEs are spatially-grouped and the under-represented edge UE groups, having the least *assignable* resources, are prioritized for CA. This results in assigning the best channels to the edge groups. The frequency resources are scheduled to the groups based on inter-group and intra-group Proportional Fair Packet Scheduling (PFPS) in the time and frequency domains respectively, to resolve resource contention. The proposed approach outperforms the existing channel-blind Round-Robin and channel-aware Opportunistic CA, in terms of overall uplink throughput, by 33% in CC assignment and 21% in PFPS, in addition to significant throughput improvements for the edge UEs.**

***Index Terms*—Carrier Aggregation, Uplink, spatial groups, Component Carriers, Assignment, Scheduling**

I. Introduction

3GPP LTE-A or Long Term Evolution-Advanced targets to achieve peak uplink and downlink data rates of 500 Mbps and 1 Gbps, respectively, for low-speed UEs and around 100 Mbps for those with higher mobilities. It accommodates the next generation of telecommunication services such as real-time high-definition video streaming, mobile HDTV and high-quality video conferencing. In LTE-A systems, the bandwidths in both uplink and downlink can go upto 100 MHz, which is achieved by Carrier Aggregation (CA) or aggregation of individual Component Carriers (CCs).

Fig 1 shows the Radio Resource Management (RRM) framework [1] of a multi-carrier LTE-A system with the aggregation of three CCs. The Evolved Node B (eNB) performs session admission control, based on the QoS requirements and service class priorities of different UEs. Layer 3 carrier load balancing involves assignment of different CCs to the UEs.

978-1-4673-1239-4/12/$31.00 ©2012 IEEE

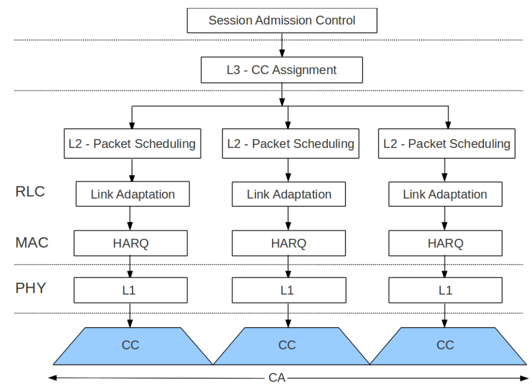


Fig. 1: Radio resource management framework of an LTE-A system

Layer 2 Packet Scheduling (PS) deals with allocating the time and frequency resources to the different UEs that are multiplexed on each CC (pointed by the physical Layer I).

Different UEs at different geographical locations often experience diverse channel conditions, due to factors like multipath propagation, shadowing, etc. The existing CC assignment techniques, such as round-robin and mobile hashing, are channel-blind and do not account for these variations. For example, UEs present at the cell-edges, termed edge UEs, have less CCs with good channel quality than those at the cell-center. The latter have enhanced Modulation and Coding Scheme (MCS) levels, which result in higher data rates, facilitated by increased bandwidths. Therefore, even if both the edge and center UEs have the same traffic requirements, assignment of equal number of CCs to them leads to unfairness.

This deficit becomes more critical when UEs possess varying traffic requirements, especially when the edge UEs contribute to a bulkier data traffic (such as video streaming) than the center UEs (say FTP file transfer). If the CC assignment mechanism follows a channel-blind round-robin or an opportunistic algorithm (in which the center UEs are prioritized due to their higher channel access probabilities), the eNB could eventually exhaust the small choice of frequency resources, *assignable* to the edge UEs, by allocating them to others. Though appropriate scheduling would be able to resolve the contention claim of common resources amongst the UEs, an efficient CC assignment mechanism is important to maximize the system throughput.

This paper assumes stationary or low-speed mobile UEs.

The UEs are grouped based on spatial correlation [2], [3], such that UEs close to each other have similar channel conditions. In order to minimize the probing overhead from the UEs to the eNB, only one representative UE from a group is chosen to feedback CQI to the eNB on behalf of the entire group, as in [2]. Due to similar channel conditions within a group, the CQI feedback from one representative UE, indeed, reflects the state of the channel conditions experienced by the entire group. Further, the above-identified issues are addressed in this work by the following key contributions:

- **Edge-prioritized Channel- and Traffic-aware CC assignment**: The under-represented edge UE groups are prioritized in CC assignment for fairness. This prioritization helps to achieve higher cell-edge and overall uplink throughput in CC assignment and thus, the under-represented cell-edge groups get a better representation. A theoretical model based on the Generalized Assignment Problem (GAP) is used for this purpose.
- **Profile-based Proportional Fair Packet Scheduling (PFPS)**: Contention of frequency resources amongst groups is resolved using time-domain PFPS, involving relevant group-based priority metrics. The Physical Resource Blocks (PRBs) of the aggregated carrier, assigned to a group, are scheduled to its UEs using frequency-domain PFPS.

Power optimization at the UE is beyond the scope of this paper. It is assumed that power budget of UEs allow them to be assigned over an aggregated carrier comprising more than one CC for increased bitrates. Also, spatial grouping, as mentioned above, leads to reduced CQI feedbacks and hence, power savings in the UEs. The main reason to prioritize the under-represented edge UE groups is that they have only limited number of CCs with good channel quality due to higher path loss at the cell-edges and log-normal shadowing. When edge UEs contribute to substantial traffic, it is imperative that these limited CC choices are assigned to them. This prevents the edge UEs from resource starvation. Proportional Fair Packet Scheduling (PFPS) prioritizes those groups and UEs, whose requirements are least satisfied, thus contributing to fairness. By the above two proposed mechanisms, this paper proposes to enhance the throughput of the cell-edge UEs and thereby, claims to improve the overall uplink system throughput, as is evident from the simulation results.

The rest of the paper is organized as follows: Section II provides an overview of the state of the art. Section III discusses the system model. Sections IV and V delineate the proposed CC assignment, inter- and intra-group scheduling techniques. The simulation results are evaluated in Section VI. Section VII throws some insights on power control optimization and highlights some of the limitations in the proposed mechanisms. Conclusions and future research directions are provided in Section IX.

II. Review of Existing Literature

In [1], a cross-CC PFPS is proposed to improve the coverage, performance and enhance the fairness in allocating resources to the UEs. Both LTE Rel 8 and LTE-A UEs are considered in the envisioned scenario. The authors consider assigning all the CCs in the available frequency spectrum to an LTE-A UE, but only one CC to each LTE Rel 8 UE, based on CC load balancing methods, such as round-robin and mobile hashing. The authors use the traditional Proportional Fair Packet Scheduling (PFPS) mechanism [4] in which any Physical Resource Block (PRB) of a CC is allocated to the UE, which has the maximum scheduling metric value on that PRB. The CC assignment considered in [4] is channel-blind and the authors do not account for varying traffic requirements of each UE. In [5], PFPS scheduling for LTE in the uplink is explored, considering the contiguous allocation of sub-carriers and resource blocks to the UEs, supported by Single Carrier-FDMA. The time-domain PF algorithm, discussed in [4], is adopted in the frequency-domain setting. The authors show the NP-hardness of the frequency domain scheduling under contiguous allocation and present four heuristic scheduling algorithms. They consider ordering the UEs based on their PF metric values with respect to the resource blocks and the vice-versa, channel characteristics of the resource blocks such as SINR and grouping the resource blocks based on highly-correlated CQI values. As discussed in Section I, PFPS scheduling is discussed in our paper but, from the perspective of scheduling the resource blocks in an aggregated carrier.

Inter-band CA, aggregating CCs from different frequency bands, is discussed in [6], [7]. In [6], different CCs belonging to non-adjacent frequency bands are assigned for CA. The CC assignment follows a channel-aware mechanism based on the path loss of the CC. As the UEs could not be scheduled on each CC, the authors form groups of UEs and propose a modified UE group-based PFPS, instead of the traditional PFPS technique. The grouping of the UEs based on spatial channel modeling is discussed in [3]. They consider channel access probability of the groups to be directly proportional to the number of CCs, on which they are assigned. However, this could possibly result in resource starvation for cell-edge UEs. In [7], downlink resource allocation for inter-band CA is investigated to assign different CCs to the UEs. The authors take into account radio channel characteristics such as the propagation path loss, inter-cell interference, etc. Whilst our paper also discusses inter-band CA, the scenario is in the uplink, which involves grouping the UEs, prioritizing the under-represented ones and scheduling the resource blocks. Notions of primary cell and secondary cells are also discussed.

In [8]–[10], the authors consider CA in the uplink. An investigation on the outage probability of cell-edge UEs is carried out in [8]. They incorporate a weighting factor in cross-CC PFPS metric [1], by which cell-edge UEs achieve better fairness. The RRM framework in terms of channel-blind CC load balancing and Adaptive Transmission Bandwidth (ATB)-based PS [11] is discussed in [9], [10]. They reduce the UE transmission power by an offset equal to the value by which the total transmission power exceeds the maximum power limit. But this could adversely affect the cell-edge UEs due to their lower Signal-to-Interference-plus-Noise Ratio (SINR) values. A channel-aware PS algorithm based on ATB is proposed in [11]. This paper proposes a metric for scheduling the PRBs to the UEs in the uplink. This approach schedules

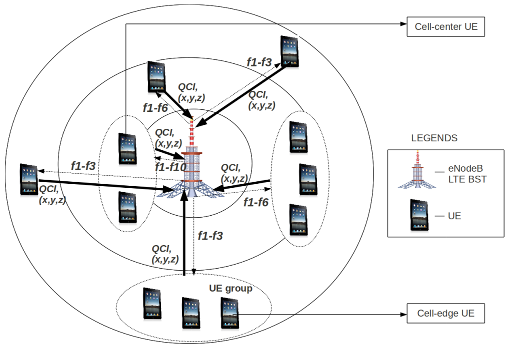


Fig. 2: Cell structure illustrating sample grouping of UEs based on geographical location and available CCs for each group, selected from range $\{f_1, ..., f_{10}\}$

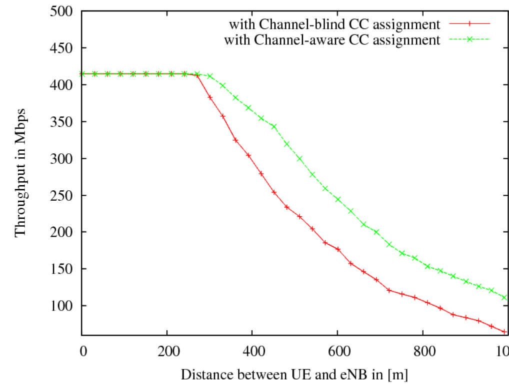


Fig. 3: Improvement of channel-aware path-loss based CC assignment over channel-blind Round-Robin CC assignment. Channel-aware scheme obtains around 57% improvement in throughput for cell-edge users with an overall improvement of 41%

a PRB group on the UE with the highest scheduling metric on it and expends its bandwidth as long as its metric with the UE remains highest, following which the next UE is chosen and so on. The process is repeated until all the PRB groups are allocated to the available UEs. ATB holds relevance in the intra-group PFPS, discussed in our paper.

III. System Model

This paper considers uniform distribution of UEs throughout the cell (see Fig 2 for an illustrative example). The base station or eNB performs spatial grouping of the UEs and determines the QoS requirements of each group. A default Evolved Packet System (EPS) bearer is activated for every UE registered in the system. The UEs use this bearer to send their location information in the form of GPS coordinates (x, y) and altitude z (supported by the Enhanced-911 services [2]) and QoS traffic profile information to the eNB. The QoS traffic profile information is indexed using the QoS Class Identifier (QCI), probed to the eNB in Fig 2, and its corresponding parameters are detailed in [12]. eNB uses the GPS coordinates to group spatially-correlated UEs and the QoS profile information to determine the net traffic requirements of the group. Grouping is performed based on the normalized covariance, the distance between the UEs and the standard deviation of the shadow fading [2], [3]. The UEs within a group have larger spatial covariance and similar channel conditions. So, one representative UE is elected to probe CQI on behalf of the entire group to reduce the probing overhead. Based on the current resource availability in the cell and priority levels of the new EPS bearer requests, the eNB decides upon session admission. Non-adjacent inter-band frequencies are considered for CA[1] and allocation of resources to the UEs. 10 CCs are chosen ranging from 700 MHz (f_1) to 3400 MHz (f_{10}). The CC resources corresponding to each frequency band are allocated to the UEs based on their path loss values. The path loss computation for a CC x (f_x in MHz) with respect to any UE r at a distance d_r (kms) is as follows [6]:

$$PL_{r,x} = 58.83 + 37.6log_{10}(d_r) + 21log_{10}(f_x) \quad (1)$$

The CCs, whose path loss values are less than a pre-defined threshold, are termed as *good* CCs. The prime motivation behind a path-loss based CC assignment is ensuring that the UEs are assigned onto *good* CCs. Else, they will have to increase their transmission power to mitigate the interference caused in an assigned lossy channel(s). Assignment of *good* CCs is not guaranteed in a channel-blind scenario. In Fig. 2, $f_a ... f_b$ from the eNB to a UE indicates that the set of CCs belonging to frequency bands, ranging from $f_a ... f_b$, are *good* CCs to the UE.

Simulations were conducted to study the improvement of channel-aware path loss-based CC assignment over channel-blind round-robin CC assignment. A set of LTE-A UEs move from the cell center (0 km from the eNB) towards the cell edges (1 km from the eNB) at a low speed in different directions (radially towards the cell-edge). As shown in Fig 3, there is 41% improvement in throughput due to path loss-based CC assignment over round-robin CC assignment and this improvement is more towards the edges, due to higher channel fading characteristics. This trend at the cell-edges is the key motivation for us to propose an edge-prioritized CC assignment.

For experimental evaluation, all the UEs are configured with an equal transmitting power on all the frequency bands. Similarly, the eNB is also configured with an equal transmitting power on its frequency bands. The computations of SINR, Channel Quality Indication (CQI) value and channel capacity rates on the PRBs of all the CCs are done, based on model proposed by [2]. The spectral efficiency on any PRB q on CC x, $\gamma_{q,x}$, is computed as follows [13]:

$$\gamma_{q,x} = log_2 \left(1 + \frac{SINR_{q,x}}{-ln(5 * BER_{q,x})/1.5} \right) \quad (2)$$

where $BER_{q,x}$ is the accepted Block Error Rate on the q^{th} PRB of the x^{th} CC. The spectral efficiency decides the transport block size which further determines the allocated data rates over the PRBs.

[1]Though inter-band carrier aggregation requires a complex antenna design, it has advantages from the deployment perspective: The service providers are usually allotted component carriers over many small frequency bands during spectrum auctioning and not necessarily one contiguous band. We later discuss the primary cell and secondary cell notions that arise out of inter-band CA in section IV

It is to be noted that the proposed mechanisms are preferably applicable from an uplink perspective. This is because assigning CCs with a higher path loss would require higher transmission power for the UEs. Power is an important concern for all mobile devices with limited battery life. On the other hand, in the downlink scenario, the same would be a concern for the eNBs, which are not so power-limited as the UEs. Even if UEs have to receive data on lossy channels, the power consumed for receiving data is less, when compared to data transmission on such channels.

IV. Carrier Aggregation

When a UE is contributing to multiple traffic applications, the aggregate of the Maximum Bit Rate (MBR) requirements of each of them is termed as the Aggregate Maximum Bit Rate (AMBR). Here, the AMBR requests of a spatial group are considered for CA as a whole. The traffic requirements of a group are defined in Section IV-B. In this paper, the process of aggregating the CCs and assigning them to the spatial UE groups, based on their traffic requirements, is modeled as an NP-Hard Generalized Assignment problem [14], as follows:

Formulation: Given a set of n items (Component Carriers) $X = \{x_1, x_2, ..., x_n\}$ and m bins (spatial groups) $G = \{G_1, G_2, ..., G_m\}$, where each bin G_i is associated with a budget (required bandwidth) W_i, then for any G_i, if each x_j has a profit (estimated throughput) p_{ij} and a weight (bandwidth) β_{ij}, the solution is the subset of items (aggregated carrier) U and the assignment from U to the bins. A feasible solution is a solution in which for each bin (group) G_i, the solution's profit is the sum of profits (achieved throughput) for each item-bin (CC-group) assignment. The goal is to find a maximum profit feasible solution with minimal cost.
Here, β_{ij} is the net bandwidth obtained in the event of assigning CC x_j to G_i, considering the channel losses. The heuristic employed to solve this involves two steps: (i) prioritizing the spatial UE groups and (ii) CC assignment.

A. Prioritizing the spatial groups

The distribution of the good CCs to the UEs in a cell is illustrated in Fig. 4. Due to path loss, shadowing and channel fading effects, the number of good CCs for UEs is maximum at the cell center and minimum at the cell edges. The algorithm takes into consideration, the above-discussed distribution of good CCs to the UEs. It orders the CCs of the frequency bands, ranging from the lowest frequency to the highest, in the order of increasing path loss. Then, it orders the groups in the following manner:
Let $\hat{X}_{r,i} \subseteq X$ be the set of good CCs for user r in group G_i, such that $\forall x \in \hat{X}_{r,i}, PL_{r,x} \leq PL_{Th}$. So, the set of good CCs for the group is:

$$\hat{X}_i = \bigcup_{r \in G_i} \hat{X}_{r,i}$$

The priority metric for group G_i, M_{G_i}, is given by:

$$M_{G_i} = c.\left(\frac{1}{|\hat{X}_i|}\right)$$

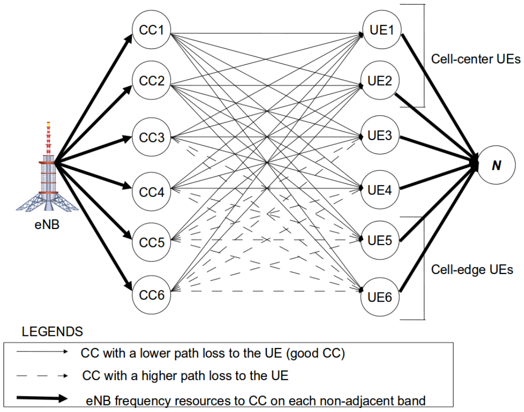


Fig. 4: Distribution of good CCs to the UEs. CC1, CC2, ... CC6 are arranged in increasing frequency

where c is a proportionality constant. The rationale behind such an ordering is to prevent exhaustion of resources for the UE groups with limited choices of *assignable* CCs, such as those at the cell edges.

Proof: We prove that the above ordering is a near-optimal prioritization of UE groups for CC assignment, by the principle of induction. Let the groups obtained from the above order (in sequence) be:

$$G^{\star} = \{G_1, G_2, ..., G_m\}. \tag{3}$$

Base case $k = 1$: The base case, where the first group $\tilde{G_1} \in G^{\star}$ is selected for priority is *trivially* true, as at that instance, it would have the *least* number of good CCs per UE.
Inductive Case $k > 1$: Assuming that the first k steps, choosing $\tilde{G_1}, \tilde{G_2}, ..., \tilde{G_k}$, are correct, we need to prove that the $(k+1)^{th}$ step is also correct.

Let $U_k \in \hat{X}_k$ be the aggregated carrier set assigned for group $\tilde{G_k}$. Let V_l^{PRB} be the set of available PRBs on the l^{th} CC. It is to be noted that only good CCs are assigned to the UEs, as discussed in Section III. We define χ as the set of remaining CCs:

$$\chi = X - \bigcup_{j=0}^{k-1} U_j, \text{ such that } \forall l \in U_j, V_l^{PRB} = \{\emptyset\}.$$

The aggregated carrier set for $\tilde{G_k}$ is chosen from χ. For contradiction, let us assume that the $(k+1)^{th}$ step is false. Then, $\tilde{G_k}$ and $\tilde{G}_{k+1}$ are the first pair of out-of-order groups. But, $\hat{X}_{k+1} \subset \hat{X}_k$ from Eqn. 3. So, in the worst case, if $U_k = \hat{X}_{k+1} \bigcap \chi$, then,

$$U_{k+1} = \{\emptyset\} \tag{4}$$

and $\tilde{G}_{k+1}$ should be scheduled to resolve this contention. On the other hand, if the $(k+1)^{th}$ step is true i.e. $\tilde{G}_{k+1}$ is served before $\tilde{G_k}$, then even if $U_{k+1} = \hat{X}_{k+1} \bigcap \chi$,

$$U_k \neq \{\emptyset\} \tag{5}$$

and it can be assigned at least one CC.

From Eqns. 4 and 5, Eqn. 4 has a greater adverse impact. Thus, the assumption is false and the $(k+1)^{th}$ step is true, indicating that the groups are served as in their order in $G^{\star}$. This argues that as the number of good CCs become higher, upon moving towards the center, even if the cell-center UEs are least-prioritized in assignment, they could still be allocated onto good CCs, as in Eqn. 5.

B. CC assignment

Having prioritized the UE groups, the next step is to assign the CCs to the UEs in the order of the priority metrics of their respective groups. The assignment is done based on the traffic requirements of the UEs in each group and the available bandwidths of its *good* CCs. Mathematically, the problem is formulated as follows:

$$\text{For each spatial group } i, \ \min \sum_j y_{ij}\beta_{ij} \geq W_i$$
$$\text{subject to: } 0 \leq \textstyle\sum_j y_{ij} \leq 1$$

where, y_{ij} is the fraction of the total number of PRBs in CC j allocated to group G_i, β_{ij} is the available bandwidth in CC j for group G_i, considering the loss factor due to path loss, shadowing and multi-path Rayleigh fading and $W_i = \sum_{r \in G_i} w_r$, where, w_r is the estimated bandwidth of UE r in group G_i based on its AMBR requirements.

The purpose of an effective CC assignment i to allocate the *best* channels to under-represented cell-edge UEs, enhance the net uplink system throughput and increase the Guaranteed Bit Rate (GBR) values of the traffic applications (thereby promising higher goodput). The traffic requirement of any group G_i is given by:

$$R_i = min\left(\sum_j \beta_{ij}, W_i\right), \tag{6}$$

In Eqn. 6, $j \in \hat{X}_i - \bigcup_{k=1}^{i-1} U_k$ and U_k is already defined in Section IV-A. Once the traffic requirements of the groups are determined, the estimated number of CCs to be aggregated and the PRBs to be assigned from each CC are computed, based on the Channel State Information (CSI) feedback probed by the representative UE of the group based on its path loss, shadowing and multi-path fading values on its set of good CCs. As this paper focuses on LTE uplink, the PRBs should be assigned contiguously to the UEs. From these information, the eNB estimates the Signal-to-Noise-Ratio (SINR), Channel Quality Indication (CQI) and the spectral efficiency values for the PRBs on each good CC. The appropriate spectral efficiency for G_i on a good CC j is determined as $\kappa_{i,j}$. The Transport Block Size (TBS) and the throughput of the users of group G_i on CC j are estimated based on $\kappa_{i,j}$. This throughput estimate is used to determine the number of CCs to be assigned to every UE group, along with the total number of PRBs of each CC. The aggregated carrier for the group is the set of these assigned CCs along with the PRBs on each CC. And, the set of spectral efficiency values for group G_i on its entire set of good CCs is $\{\kappa_i\}$. It can be written as the following recursive function:

Base case:

$$U_1 = \arg\max_{U_1} \left(f\left(R_1, \{\kappa_1\}, X\right)\right)$$

Recursive Case:

$$U_i = \arg\max_{U_i} \left(f\left(R_i, \{\kappa_i\}, X - \bigcup_{j=1}^{i-1} U_j\right)\right)$$

where, the first parameter R_i is the traffic requirement of G_i (see Eqn. 6) and the third parameter is the remaining number of available CCs for CC assignment to G_i. The function $f()$ returns the aggregated carrier set U_i, yielding maximum throughput by aggregating the minimum adequate number of CCs using spectral efficiency value set κ_i to satisfy the traffic requirements R_i. In the above recursive case, $\forall j_{j=1}^{i-1} V_j^{PRB} = \{\emptyset\}$. The total channel capacity C_i obtained as a result is:

$$C_i = \sum_{\hat{X}_j \in U_i} \sum_{\tilde{q} \in \hat{X}_j} \mathrm{BW}_{\tilde{q},j} \log_2(1+\alpha\psi_{\tilde{q},j}) \ , \ \alpha = \frac{-1.5}{ln(5 \times BER)} \tag{7}$$

where $BW_{\tilde{q},j}$ is the bandwidth offered by $\tilde{q}^{th}$ PRB on the j^{th} CC $\hat{X}_j$ of the aggregated carrier U_i, α is the SNR gap [6], and $\psi_{\tilde{q},j}$ is the estimated SINR value for PRB according to QoS traffic class requirements.

Of course, there could be another group G', whose good CCs could have already been allocated to previous high-priority groups such that $U_{G'} = \{\emptyset\}$. There can also be certain other groups whose available set of good CCs are not sufficient enough to satisfy their traffic requirements. Each of such groups will have to be scheduled with another group, whose aggregated carrier contains the majority of the good CCs of G'. The proposed edge-prioritized CC assignment mechanism is sequentially finalized in Algorithm 1.

The Primary cell for any group G_i is that CC in its inter-band aggregated carrier U_i, which has the least path loss and the most number of PRBs, assigned to any UE in G_i. The rest of the CCs in U_i are the secondary cells for G_i.

V. Scheduling

In the CC assignment, it is possible that the assigned CCs may not be sufficient to serve its traffic requirements. This situation arises when two or more groups contend for a common set of good CCs. Such claims over the common set of CCs are not accounted for in CC assignment, discussed above. The frequency resources allocated to a group would also be subject to contention amongst the UEs within the group. Scheduling tries to resolve this contention by splitting the time and frequency resources across the groups and UEs, respectively.

This paper employs PFPS techniques in the time-domain to resolve contention amongst the groups and in frequency-domain to split the commonly-claimed PRBs amongst the UEs. The most important difference between uplink and down-link scheduling is with respect to the allocation of the PRBs. As this paper deals with uplink CA, PRB groups comprising only contiguous sub-carriers should be scheduled to the UEs.

Algorithm 1 Proposed Edge-prioritized CC assignment

Begin Proc{**Edge-prioritized CC assignment**}
Order the set of CCs, $\{X\}$, in the increasing order of the frequency of their bands.
for all UE r in the cell **do**
  Receive GPS coordinates and QoS profile information.
  Determine path loss on each CC in the available set of CCs, $\{X\}$, as in Eqn. 1, shadowing and penetration loss values.
  Determine the set of good CCs for UE r.
end for
Form a set of spatially-correlated groups of UEs, G.
for all UE group $G_i \in G$ **do**
  Compute the net traffic requirement of the group as W_i, such that $W_i = \sum_{r \in G_i} w_r$.
  Determine the set of good CCs for G_i as $\hat{X}_i$.
end for
Prioritize the groups in G in non-decreasing order of their number of good CCs, forming a set $G^\star$.
Set $\chi := X$
for all UE group $G_i \in G^\star$ in sorted order **do**
  for all CC $x_j \in \hat{X}_i$, such that $x_j \in \chi$ and $V_j^{PRB} \neq \{\emptyset\}$ **do**
    Add CC x_j to U_i
    Estimate the SINR, CQI for every PRB $v \in x_j$ with respect to G_i
    Determine spectral efficiency for G_i on CC x_j as $\kappa_{i,j}$
    Compute the number of contiguous PRBs to be allocated to G_i from each CC x_j based on $\kappa_{i,j}$ and W_i, as U_j^{PRB}
    Allocate them to G_i. Set $V_j^{PRB} := V_j^{PRB} - U_j^{PRB}$
    if $V_j^{PRB} = \{\emptyset\}$ **then**
      Set $\chi := \chi - \{x_j\}$
    end if
  end for
end for
End Proc{**CC assignment**}

A. Inter-group scheduling

A time-domain inter-group scheduling mechanism is used to handle the contention arising when the two or more CCs are common to more than one group and the highest-prioritized group is assigned these CCs, leaving less or no *assignable* CCs to other contending groups to meet up with their traffic requirements. The time slots in a single uplink LTE frame are split amongst contending groups using Required Activity Detection (RAD) [12]. The algorithm determines the scheduling on the common CCs at the next time slot t by taking into account, factors such as wideband achievable throughput of the contending groups on the aggregated carrier, past achieved throughput of the groups over the aggregated carrier and over the scheduled Transmission Time Intervals (TTIs), and their AMBR values. It computes the scheduling metric of each group, during every time slot of an uplink LTE frame and schedules common CCs to the group with the highest metric value. A group with higher but less-satisfied traffic requirements gets a higher priority.

The group G_i which has the maximum value for the TD scheduling metric (TDSM) on U_i at t would have access to the aggregated carrier U_i at time slot t.

$$G_i = \arg\max_{G_i} \{TDSM_{i,t}\} \tag{8}$$

$$TDSM_{i,t} = \left(\frac{D_{i,t}}{\overline{Z}_i} . \left(\frac{AMBR_i}{\overline{Z}_i^{TTI}} + S_{i,t} \times C'_{i,t} \right) \right) \tag{9}$$

where, $D_{i,t}$ is the instantaneous wideband achievable throughput for G_i over its aggregated carrier U_i at time slot t, $\overline{Z}_i$ is its past average throughput over U_i, $\overline{Z}_i^{TTI}$ is the past average throughput over the Transmission Time Intervals (TTIs) in current frame, $S_{i,t}$ is its share of excess capacity at time t made proportional to W_i, and $C'_{i,t}$ is the excess capacity left in U_i at time t, after the minimum QoS is fulfilled for G_i.

B. Intra-group scheduling

In this subsection, the scheduling of PRBs to individual UEs within a group in frequency domain is discussed. As the LTE uplink is based on SC-FDMA, we consider allocation of only contiguous PRBs to the UEs. The scheduling follows a Frequency Domain PFPS making use of an AMBR-based FD metric. The PRBs, forming a PRB group, are allocated to a UE with the maximum scheduling metric on the group. Its bandwidth is expended for the UE, until another UE with a higher FD metric, is scheduled on that PRB group. Here, each UE is allocated different number of PRBs based on its traffic requirements. The FD scheduling metric for each UE is given as follows:

$$\text{FDSM}_{r,i,t} = \left(\frac{AMBR_r}{\overline{Z}_{r,i}} \right) \tag{10}$$

where $\overline{Z}_{r,i}$ is past average throughput for UE r on U_i. The UE in G_i, with larger but least-satisfied traffic requirements, is thus prioritized for PRB scheduling at the next TTI t.

$$\text{UE}_r = \arg\max_{r \in G_i} \{\text{FDSM}_{r,i,t}\} \tag{11}$$

Once the UE is chosen, the PRB group over which it has to be scheduled, is selected as follows:
Let the number of PRBs in U_i be V_i^{PRB}. Let the number of PRBs required to be assigned to any UE $r \in G_i$ be v_r^{PRB}. Let l_v be the number of UEs requiring the same number of PRBs v. The total number of ways, the PRBs of the respective UEs can be scheduled is $\frac{|G_i|!}{\forall v \prod_v l_v}$. Now, the total number of possible combinations of the PRB groups for the arrangements of the group members is given by :

$$Q = \frac{|G_i|!}{\forall v \prod_v l_v} \binom{|G_i| + (V_i^{PRB} - \sum_{r=1}^{|G_i|} v_r^{PRB})}{|G_i|} \tag{12}$$

The PRB set of these combinations is given by $\{U^Q\}$. Now, the best PRB group for UE r out of the Q combinations is selected as the one, matching its traffic requirements and over which, its wideband achievable throughput is maximum. The steps are finalized in the algorithm, below:

Algorithm 2 Proposed intra-group scheduling

1: Begin Proc{**Intragroup_FDPS**(U^Q, G_i, t)}
2: Choose the UE r with the highest scheduling metric: $r = \arg\max_r\{FDSM_{r,U_i,t}\}$, such that $r \in G_i$
3: Select the set $U^{Q_c} \in U^Q$ such that $U^{Q_c} = \arg\max_{U^{Q_c}}\{D_{r,q,t}\}$, $\forall q \in U^{Q_c}$ and $|q| = v_r^{PRB}$
4: Allocate PRB group q to UE r at TTI slot t
5: *Intragroup_FDPS*($U^{Q_c}, G_i - \{r\}, t$)
6: End Proc{**Intragroup_FDPS**}

The UE r with maximum scheduling metric at time slot t is allocated the q^{th} PRB group contained for r (i.e., $|q| = v_r^{PRB}$) in the set of combinations $U^{Q_C} \subseteq U^Q$, over which its wideband achievable throughput ($D_{r,q,t}$) is maximum. The algorithm is applied over U^{Q_c} for the next UE with the highest metric and so on, recursively. The CC assignment mechanism is repeated every LTE uplink frame to accommodate the newly-arriving UEs in the cell.

Service class Prioritization

During inter-group scheduling, the UE groups with a higher priority are granted those CCs, which may be in contention with the other groups. In such a case, the traffic requirements for the other groups would not be satisfied fully. Here, the UEs in the remaining groups should select only a subset of their traffic applications and suspend the rest for the next TTI slots. This could be done based on metrics such as traffic priorities, packet delay budget, packet error rate, etc. In this paper, the least-prioritized traffic class of every UE in the group G_j, which has lost its contention with the scheduled higher-priority group G_i, is suspended until the next TTI. Then, it should be checked whether the chosen set of applications can be scheduled over the remaining set of CCs for G_j. If not, the above steps are repeated until the condition is satisfied. The LTE application-specific priorities are given in [12].

VI. Performance Evaluation

The proposed schemes are implemented in the discrete-event Network Simulator NS3. An LTE simulation model, code named LENA (LTE/EPC Network simulAtor) [13], is used for the simulation purposes. The salient features of this simulation model include fully-implemented uplink PHY and MAC functionalities, such as Adaptive Modulation and Coding (AMC), path loss measurements, channel state information feedbacks. These features are extensively used in our simulation for modeling the channel-awareness aspects of our proposed approach. The LTE model also has provisions for modeling different GBR and non-GBR applications. We consider GBR applications with high-end formats and higher maximum bit rates, as tabulated in Table I, in the above categories to effectively utilize the sophisticated bandwidth and scheduling techniques of LTE-A.

TABLE I: Application-specific maximum bit rates

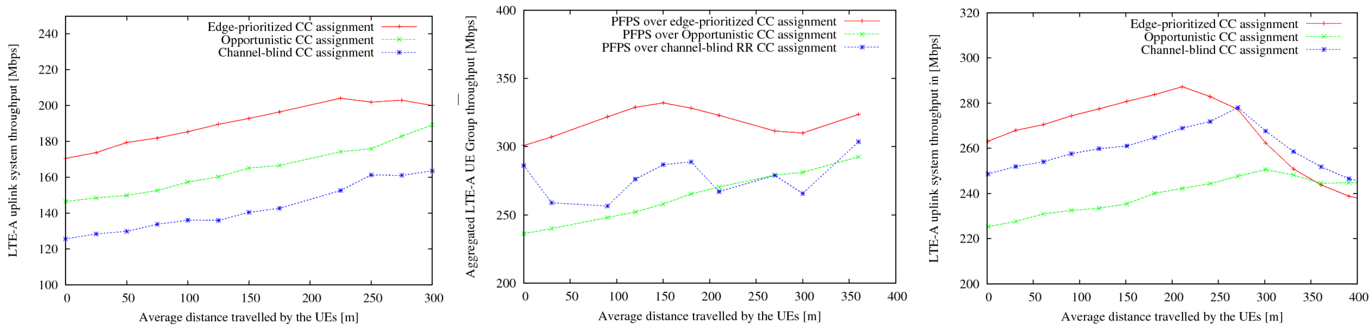
Application	Format	Value
GBR_CONV_VOICE	Direct Stream Digital	5.4 Mbps
GBR_CONV_VIDEO	High-definition Video	25 Mbps
GBR_GAMING	Real-time HDTV streaming	15 Mbps
GBR_NON_CONV_VIDEO	Blu-ray Disc	40 Mbps

TABLE II: NS3 Simulation Parameters

Parameter	Value
Cell Size	1 km
No. of non-adjacent frequency bands	10
Frequency bands	From 700 to 3400 MHz
Number of PRBs on each CC	From 8 (1.4 MHz-FDD) to 110 (20 MHz-FDD)
eNB (Node) Mobility Model	Constant Position (Stationary)
UE (Node) Mobility Model	Constant Velocity
UE traffic applications	GBR applications
UE distribution in the cell	Uniform
No. of UEs	Max. 10 per cell (Max. 5 traffic applications per UE)
Loss Model	Jakes Fading Model
Lognormal shadowing	Gaussian distribution with standard deviation 7.5 dBm
Avg UE T_x power	23 dBm
Avg eNB T_x power	43 dBm
Noise spectral density	-174 dBm/Hz
Antenna configuration	1x1
Threshold path loss	-120 dBm

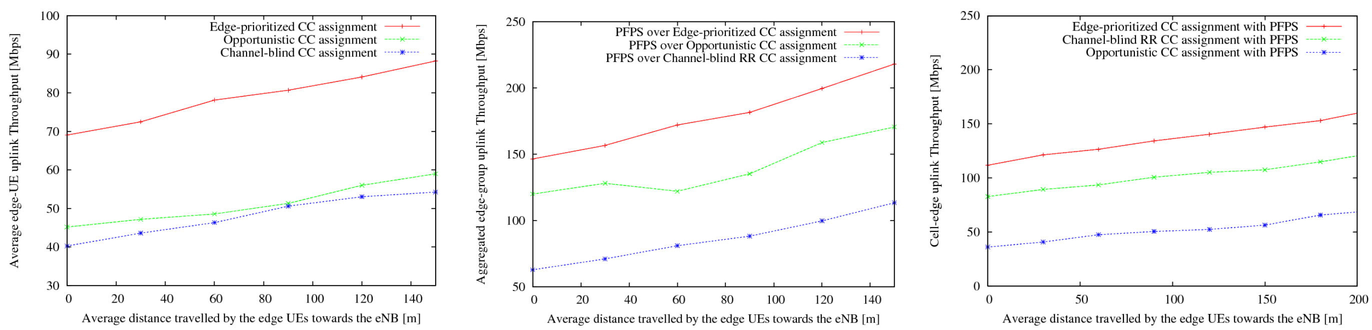
The performance of the proposed mechanisms is evaluated in terms of the average individual LTE-A uplink throughput, aggregated UE group throughput, edge UE throughput and achieved peak GBR. A Cumulative Distribution Function (CDF) on the uplink throughput achieved as a result of edge-prioritized CA is also considered for evaluation. The simulation parameters are as shown in Table II and the results shown in the graphs are averaged over multiple trials. The UEs are distributed uniformly throughout the cell and configured with low mobility of maximum 10 ms^{-1}. The UEs, at a distance of beyond 500m from the eNB, move towards the base station, and those, at a distance of within 500m move away from the base station. The simulation is carried out until each UE reaches the 500m distance from the eNB. The low mobility enables to observe the trends caused due to the variation of their distance-dependent path loss values. Two cases of uplink traffic distribution is considered: one, where all the UEs contribute to approximately the same traffic and two, where the edge UEs contribute to more traffic than those at the cell center.

Fig 5a evaluates the average aggregated LTE-A uplink throughput on heterogeneous traffic applications as against the average distance travelled by the UEs. The simulation accounts for uniform UE distribution throughout the cell and a larger traffic distribution from the cell-edge UEs (inverse Gaussian distribution). The trend indicates a gradual increase in the throughput of the system, as the edge UEs move towards the center (even as the center UEs move towards the edges). Hence, the performance of the edge UEs implies a higher significance in the overall throughput. The graphs



(a) CC assignment (b) Inter & Intra-group PFPS (c) CC assignment in a uniform traffic scenario

Fig. 5: Aggregated LTE-A uplink throughput improvements with proposed scheme



(a) CC assignment (b) Inter & Intra-group PFPS (c) CC assignment in a uniform traffic scenario

Fig. 6: Edge UEs' throughput improvement with proposed scheme

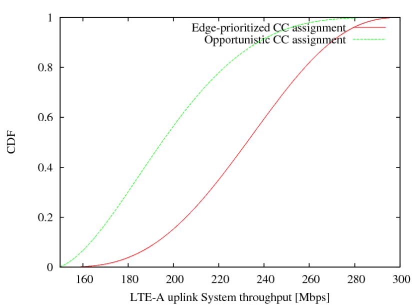


Fig. 7: CDF of LTE-A uplink throughput

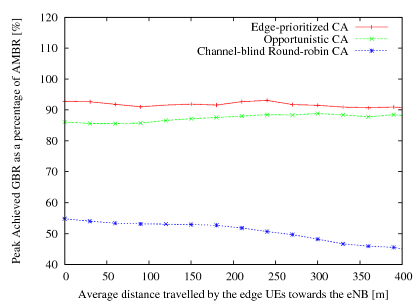


Fig. 8: Achieved GBR

indicate that an edge-prioritized CC assignment results in 33% improvement over traffic-aware channel-blind CC assignment and 15% over traffic- and channel-aware opportunistic CC assignment. The graph shows a higher improvement when the UEs are in their initial position, due to a larger benefit of the proposed mechanism to the cell-edge UEs. The cell-edge UEs record an improvement of 64% over channel-blind and 54% over opportunistic CC assignment schemes, as observed in the graph drawn in Fig. 6a.

In Fig 5b, the aggregated LTE-A group throughput as a result of employing inter-group and intra-group PFPS, as discussed in Section V, over edge-prioritized CC assignment is evaluated against PFPS over opportunistic and round-robin CC assignment mechanisms. A traffic scenario similar to the previous result is considered. Inter-group PFPS over the proposed edge-prioritized scheduling outperforms the PFPS over channel-blind round-robin assignment by 15% and PFPS over opportunistic assignment by 21%, on an average. Comparing this with the one observed in Fig 5a, PFPS tries to enhance the throughput in opportunistic CC assignment than it does for edge-prioritized CC assignment, due to the latter's exhibited optimality in CC assignment, as argued in Section IV. An improvement of 29% is observed for the aggregated throughput of cell-edge UE groups as a result of PFPS on edge-prioritized CC assignment over PFPS on opportunistic CC assignment. The latter, in turn, shows an improvement of 62% over PFPS upon channel-blind round-robin CC assignment. These trends are observed in the graph, shown in Fig. 6b.

In Fig 5c, a homogeneous traffic scenario is envisioned in which the UEs contribute to uniform traffic across the cell. Even as the traffic is uniformly distributed, as stated in Section I, allocation of the same number of resources would lead to unfairness due to poor channel conditions at the edges. The proposed edge-prioritized CC assignment mechanism yields a comparatively lower improvement in the LTE-A uplink system throughput, which is around 10% over the opportunistic CC assignment. Often, an edge-prioritized CC assignment results in throughput improvements at the cost of the cell-center UEs, which, in this case, also contribute to approximately the same traffic and hence, is the reason for lower improvement in the net throughput. However, it shows an uplink throughput improvement of around 32% over the channel-blind CC assignment, for those UEs present at the cell-edges, as shown in Fig. 6c.

Fig 7 shows the Cumulative Distribution Function (CDF) of the LTE-A uplink throughput in a given traffic scenario. The graphs show that the probability of the system to yield higher and consistent throughput values is more in the case of the proposed edge-prioritized CA over opportunistic CA by a higher mean of 20% and a lower standard deviation of 14%, for a set of common traffic scenarios. Fig. 8 shows the improvements in the peak achieved Guaranteed Bit Rates (GBRs), out of the AMBR requirements, due to edge-prioritized CA, as against the distance travelled by the UEs, within the cell. Edge-prioritized CA shows a peak average of 91.7% on these GBR values, whereas opportunistic CA shows 87.4% on the same.

VII. Discussion

The estimated transmission power (in dBm) for UE r on CC x is written as follows [9]:

$$P'_{r,x} = 10log_{10}(M_{r,x}) + P_{0,x} + \alpha_x.PL_{r,x} + \Delta_{MCS} + f(\Delta_{r,x}) \tag{13}$$

where $M_{r,x}$ is the number of PRBs allocated to UE r from CC x, $P_{0,x}$ and α_x are CC-specific open loop power control parameters, $PL_{r,x}$ is the path loss for UE r on CC x, Δ_{MCS} is the MCS-dependent power offset set by eNB and $\Delta_{r,x}$ is the UE and CC-specific closed loop correction value with relative or absolute increase depending on $f()$. Generally, the cell-edge UEs are the most-affected by higher power consumption due to lower SINR values and lossy channels. So, they need to increase their transmission power to fulfill their traffic requirements. However, with the formulation shown in Section IV-B, the UEs' traffic requirements are satisfied with relatively smaller values of $M_{r,x}$ and $PL_{r,x}$. Thus, from Eqn. 13, $P'_{r,x}$ is also a small value, indicating reduced power consumption.

The above-proposed mechanisms are not applicable to high-speed mobile UEs. As the variation in their channel conditions is drastic, the uplink CQI feedback information would become irrelevant for scheduling even within a shorter interval, from the time it was probed from the representative UE to the eNB. Moreover, due to a dynamic mobile scenario, a channel-aware scheduling would require coordination amongst multiple neighboring eNBs.

VIII. Acknowledgement

This work is partially supported by the National Science Foundation under Grant #1019343 to the Computing Research Association for the CIFellow Project.

IX. Conclusion

This paper focused on radio resource management framework of an LTE-Advanced system in the uplink, focusing on channel- and traffic-aware carrier aggregation, involving component carrier assignment and scheduling. Spatial grouping, edge-prioritized CC assignment and inter- and intra-group PFPS techniques are discussed extensively. The CC assignment is theoretically modelled as an NP-hard generalized assignment problem and heuristic mechanisms are prposed. An enhanced overall fairness and uplink throughput performance is achieved by the proposed schemes. As could be observed in the simulation results, the proposed scheme achieves an average improvement of 33% and 15% in the uplink throughputs, when compared to round-robin and opportunistic CC assignments, respectively. Throughput improvement of over 20% is observed when PFPS is employed, in addition to improvements in edge UE throughput. Uplink power control optimization and channel-aware CA for LTE-A multicast services in downlink are planned for future work.

References

[1] Y. Wang, K. I. Pedersen, T. B. Sorensen, and P. E. Mogensen, "Carrier load balancing and packet scheduling for multi-carrier systems," *IEEE Trans. Wireless Comm.*, vol. 9, pp. 1780–1789, May 2010.

[2] W. Lee and D. Cho, "CQI feedback reduction based on spatial correlation in OFDMA system," in *Proc. 68th IEEE VTC*, Sep. 2008.

[3] M. Gudmundson, "Correlation model for shadow fading in mobile radio systems," *Electronics Letters*, vol. 27, pp. 2145–2146, Nov. 1991.

[4] A. Jalali, R. Padovani, and R. Pankaj, "Data throughput of CDMA-HDR, a high efficiency-high data rate personal communication wireless system," in *Proc. 51st IEEE VTC*, Aug. 2000.

[5] S.-B. Lee, I. Pefkianakis, A. Meyerson, S. Xu, and S. Lu, "Proportional fair frequency-domain packet scheduling for 3GPP LTE uplink," in *Proc. IEEE INFOCOM*, Apr. 2009.

[6] S. Songsong, F. Chunyan, and G. Caili, "A resource scheduling algorithm based on user grouping for LTE-advanced system with carrier aggregation," in *Proc. Symp. Computer Network and Multimedia Technology (CNMT)*, Jan. 2009.

[7] H. Wang, C. Rosa, and K. Pedersen, "Performance analysis of downlink inter-band carrier aggregation in LTE-advanced," in *Proc. IEEE ICC*, Jun. 2011.

[8] Y. Wang, K. I. Pedersen, M. Navarro, P. E. Mogensen, and T. B. Sorensen, "Uplink overhead analysis and outage protection for multi-carrier LTE-advanced systems," in *Proc. 20th IEEE PIMRC*, Sep. 2009.

[9] H. Wang, C. Rosa, and K. Pedersen, "Performance of uplink carrier aggregation in LTE-advanced systems," in *Proc. 72nd IEEE VTC*, Sep. 2010.

[10] ——, "Uplink component carrier selection for LTE-advanced systems with carrier aggregation," in *Proc. IEEE ICC*, Jun. 2011.

[11] F. D. Calabrese, C. Rosa, M. Anas, P. H. Michaelsen, K. I. Pedersen, and P. E. Mogensen, "Adaptive transmission bandwidth based packet scheduling for LTE uplink," in *Proc. 68th IEEE VTC*, Sep. 2008.

[12] H. Holma and A. Toskala, *LTE for UMTS: OFDMA and SC-FDMA Based Radio Access*. The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom: John Wiley and Sons, 2009, ch. 4,8, pp. 63–65,190–193.

[13] N. Baldo, "LTE-EPC network simulator," http://iptechwiki.cttc.es/LTE-EPC_Network_Simulator_(LENA)#documentation.

[14] R. Nauss, "Solving the generalized assignment problem: An optimizing and heuristic approach," *INFORMS Journal on Computing*, vol. 15, pp. 249–266, Jul. 2003.