Downlink Radio Resource Allocation with Carrier Aggregation in MIMO LTE-Advanced Systems

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***Abstract*—Long Term Evolution-Advanced (LTE-A) networks exploit the Carrier Aggregation (CA) technique to achieve a higher data rate by allowing user equipments (UEs) to simultaneously aggregate multiple component carriers (CCs). Moreover, MIMO technologies have become increasingly mature and been adopted as a default choice of the 4G standards. However, most of existing studies on resource allocation with carrier aggregation do not consider the MIMO capability of UEs. In this paper, we address the spectrum resource allocation problem with consideration of UEs' MIMO capability as well as modulation and coding schemes (MCSs) selection in carrier aggregation based LTE-A systems. We formulate the problem under both *backlogged and finite queue* traffic models as an optimization model, and prove its NP-hardness. As a result, a 1/2-approximation algorithm is proposed to find a suboptimal solution of resource allocation. Simulation results show that the proposed algorithm outperforms the existing schemes, and performs fairly close to the optimal solution under the small-scale scenarios.**

I. Introduction

In LTE, each component carrier (CC) is typically partitioned into time-frequency resource blocks (RBs) that can be shared by multiple users. Several prior studies have investigated the packet scheduling problem for downlink traffic in order to efficiently assign resource blocks as well as modulation and coding schemes (MCSs) to user equipments (UEs) [1]. Recently, LTE-Advanced (LTE-A) is then proposed to adopt a novel technique, called carrier aggregation (CA), to aggregate the transmission bandwidth of multiple separate CCs. Many later works then jointly solve the CC assignment and packet scheduling problems, which is referred to as the radio resource allocation (RRA) problem, to better utilize the fragmental spectrum resources provided by carrier aggregation.

With the advancement of MIMO technologies, mobile device could now support more than one antenna. While MIMO has become a default choice for 4G standard, most of existing studies on resource allocation with carrier aggregation however mainly consider a scenario where all the user equipments (UEs) are equipped with a single antenna. Allocating spectrum resources with consideration of the MIMO capability of a base station is however more challenging because MIMO technologies support several operation modes [2], such as spatial multiplexing, transmit diversity, and beamforming, each of which helps increase the data rate, yet is beneficial for different channel conditions. The goal of this work is hence to solve the radio resource allocation problem with consideration of heterogeneous MIMO operational modes in carrier aggregation based MIMO LTE-A systems.

Most of the previous studies of radio resource management [3] [4] do not consider the MCS selection constraint, which is specified in 3GPP TR 36.912 [5]. It requires each UE to use a fixed MCS for all the allocated RBs of a CC at any transmission time interval (TTI). RRA hence needs to select a proper MCS based on the channel quality indicator (CQI) of UEs with consideration of the above constraint. For MIMO scenarios, each UE is allowed to transmit multiple Transport Blocks (TBs) concurrently in each RB. The above MCS constraint hence requires each TB of all RBs in the same CC to use the same MCS. In other words, in all allocated RBs, a TB needs to be assigned the same MCS, while different TBs can use different MCSs. Such a constraint makes the RRA problem in carrier aggregation based MIMO LTE-A systems more challenging.

To the best of our knowledge, this work is the first to allocate radio resources with carrier aggregation over a MIMO LTE-A system with consideration the MCS constraint specified in the standard. The existing works either only consider the MCS selection problem in a non-CC MIMO scenario, e.g., in [6], or only solve the RRA problem in carrier aggregation based MIMO systems without considering MCS selection, e.g., in [7]. Unlike those previous works, our major contributions are summarized as follows: 1) We formulate the joint downlink radio resource allocation and MCS selection problem for LTE-A systems with MIMO and CA configuration, 2) due to NP-hardness of the problem, we then propose a novel greedy RRA to approximate the optimal solution, and 3) we solve the problem under two traffic models: backlogged traffic and finite queue traffic. Our simulation evaluation shows that the proposed algorithm outperforms the existing schemes, and performs fairly close to the optimal solution under the small-scale scenarios.

The rest of this paper is organized as follows. Section II formulates the radio resource allocation problem for CA-based MIMO LTE-A systems. The proposed greedy is presented in Section III. We then evaluate the performance of our algorithm via simulations in Section IV, and conclude this work in Section V.

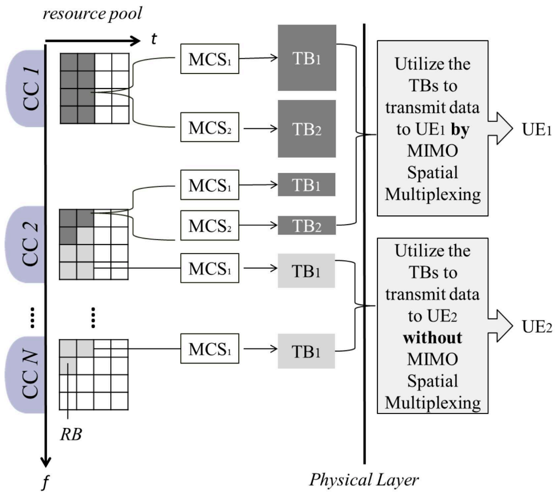

Fig. 1. Example of CC-MCS assignment for RBs per TB.

II. Radio Resource Allocator Problem

We define and formulate the radio resource allocator, i.e., RRA, problem in this section. We consider a LTE-A system with a set of UEs $\boldsymbol{M}$, a set of CCs $\boldsymbol{N}$, and a set of MCSs $\boldsymbol{C}$. Each CC includes a set of RBs $\boldsymbol{P}$, each of which can be assigned to one UE, and is 0.5 ms in time domain and 180 kHz in frequency domain. The RBs of a CC can be allocated to multiple UEs, and each UE can exploit carrier aggregation to access at most z CCs. LTE-A supports several MIMO modes [2], and our model considers three modes: SISO, transmit diversity and spatial multiplexing. Based on the LTE-A standard [1], for the SISO and transmit diversity modes, the RBs allocated to a UE form a single data unit, called Transport Block (TB), while, for the spatial multiplexing mode, the RBs allocated to a UE form two TBs, i.e., two concurrent streams, even when the UE has more than two antennas.

In addition, LTE-A forces that the RBs belonging to the same TB need to use the same MCS [5]. Namely, for spatial multiplexing, the RBs in the same TB needs to use the same MCS, but different TBs can be assigned different MCSs. Consider Fig. 1 as an example. UE1 uses spatial multiplexing with the allocated RBs belonging to the same TB assigned a distinct MCS, while UE2 uses transmit diversity with all the allocated RBs assigned a single MCS. As a result, we can collect all combinations of MCSs used by two TBs as a set $\boldsymbol{Q} := \{(l_1, l_2)|l_1 \in \boldsymbol{C} \cup \{0\}, l_2 \in \boldsymbol{C} \cup \{0\}\}$, where l_1 and l_2 are the MCSs assigned to TB 1 and TB 2, respectively. Note that, if $l_1 = 0$ or $l_2 = 0$, it means that only a single TB is allocated to the UE, i.e., the SISO mode or the transmit diversity mode. Since the channel conditions of all the RBs to each UE could be different, we assume that each UE periodically reports its Channel State Information (CSI), which includes the CQI of each RB per TB, such that the achievable rates of any given resource assignment for different MIMO modes can be computed. Then, the RRA problem considered in this paper is to assign the RBs of N CCs at each transmission time interval (TTI) to M UEs such that the system throughput can be maximized, while providing all UEs proportional fairness. Moreover, we consider the problem under two traffic models: finite queue traffic, which means the base station maintains a buffer for each UE to contain its finite traffic demand, and backlogged traffic, which means each UE has an infinite traffic demand.

To achieve high throughput while maintaining proportional fairness of spectrum resource allocation among all UEs, we adopt the Proportional Fair (PF) algorithm [8]. In particular, the PF algorithm attempts to maximize the objective function $\sum_i w_i(t)R_i(t)$, where $R_i(t)$ is the total transmission rate assigned to UE i at TTI t. The priority weight $w_i(t)$ of UE i at TTI t is defined as $1/\mu_i(t)$, where $\mu_i(t)$ is the average served transmission rate of UE i until TTI t. Such an objective function hence achieves proportional fairness by giving the UE with a lower $\mu_i(t)$ a higher priority to access the medium. Therefore, the RRA problem can be reformulated as maximizing the sum of weighted transmission rates of UEs at TTI t. To simplify notations, the TTI index t is omitted in the following model.

$$\max \sum_{i \in \boldsymbol{M}} w_i R_i = \max \sum_{i \in \boldsymbol{M}, j \in \boldsymbol{N}, k \in \boldsymbol{P}, (l_1, l_2) \in \boldsymbol{Q}} w_i x_{i,j,k,l_1,l_2} r_{i,j,k,l_1,l_2} \tag{1}$$

subject to:

$$\sum_{i \in \boldsymbol{M}, (l_1, l_2) \in \boldsymbol{Q}} x_{i,j,k,l_1,l_2} \leq 1, \forall j \in \boldsymbol{N}, k \in \boldsymbol{P} \tag{2}$$

$$\sum_{(l_1, l_2) \in \boldsymbol{Q}} \max_{k \in \boldsymbol{P}} x_{i,j,k,l_1,l_2} \leq 1, \forall i \in \boldsymbol{M}, j \in \boldsymbol{N} \tag{3}$$

$$\sum_{j \in \boldsymbol{N}} \max_{k \in \boldsymbol{P}} \max_{(l_1, l_2) \in \boldsymbol{Q}} x_{i,j,k,l_1,l_2} \leq z, \forall i \in \boldsymbol{M} \tag{4}$$

$$\sum_{j \in \boldsymbol{N}, k \in \boldsymbol{P}, (l_1, l_2) \in \boldsymbol{Q}} x_{i,j,k,l_1,l_2} r_{i,j,k,l_1,l_2} \leq D_i/T, \forall i \in \boldsymbol{M} \tag{5}$$

In the objective function, w_i is a priority weight of UE i, and x_{i,j,k,l_1,l_2} is a binary variable indicating whether UE i is scheduled on RB k of CC j with MCSs l_1 and l_2 on TB 1 and TB 2, respectively. The achievable transmission rate r_{i,j,k,l_1,l_2} of UE i using MCSs (l_1, l_2) in RB k of CC j can be computed by the following equation.

$$r_{i,j,k,l_1,l_2} = \max(t^{\text{SISO}}_{i,j,k,l_1,l_2}, t^{\text{TD}}_{i,j,k,l_1,l_2}, t^{\text{SM}}_{i,j,k,l_1,l_2})/T \tag{6}$$

, where T is the duration of a TTI and $t^{\text{mode}}_{i,j,k,l_1,l_2}$ is the information bits that can be transmitted correctly using the selected mode during T, which can be estimated based on CSI feedback. Specifically, if assigning a MCS higher than the UE's allowed rate limitation could result in a zero throughput. In addition, $t^{\text{TD}}_{i,j,k,l_1,l_2}$ differs from $t^{\text{SM}}_{i,j,k,l_1,l_2}$ because the UE could get different rates as using different MIMO modes. Finally, $t^{\text{TD}}_{i,j,k,l_1,l_2}$ and $t^{\text{SM}}_{i,j,k,l_1,l_2}$ equal zero if UE i cannot operate on MIMO modes.

The constraint in inequality (2) restricts that each RB of any CC is assigned to at most one UE. The constraint in (3) ensures that a UE can only use an MCS per TB for any of its assigned CCs. The constraint in (4) restricts that a UE can

Algorithm 1 Greedy-based CC-MCS Allocation

1: Update w_i and D_i for all UE $i \in M$
2: $\boldsymbol{U} = \{(i,j) | i \in \boldsymbol{M}, j \in \boldsymbol{N}\}$
3: $V(j,k) = 0$ for all $j \in \boldsymbol{N}$, $k \in \boldsymbol{P}$
4: **repeat**
5: Calculate $g(i,j,l_1,l_2)$ for all $(i,j) \in \boldsymbol{U}, (l_1,l_2) \in \boldsymbol{Q}$ by Algorithm 2
6: $(i^*, j^*, l_1^*, l_2^*) = \arg\max_{(i,j)\in\boldsymbol{U},(l_1,l_2)\in\boldsymbol{Q}} g(i,j,l_1,l_2)$
7: **if** $g(i^*, j^*, l_1^*, l_2^*) = 0$, **break**
8: Assign CC j^* with MCS l_1^*, l_2^* to UE i^*
9: Allocate bits to the allocated RBs R_{i^*,j^*,l_1^*,l_2^*}
10: Set $V(j^*,k) = w_{i^*} r_{i^*,j^*,k,l_1^*,l_2^*}$ for all $k \in R_{i^*,j^*,l_1^*,l_2^*}$
11: Remove (i^*, j^*) from $\boldsymbol{U}$
12: **if** UE i^* has been assigned z CCs **then**
13: Remove all pairs corresponding to UE i^* from $\boldsymbol{U}$
14: **end if**
15: **for** each $i' \in \boldsymbol{M}$ **do**
16: Let N_{i',j^*} be the set of remaining RBs of CC j^* allocated to UE i'
17: Assign $(l_1', l_2') = \arg\max_{(l_1,l_2)\in\boldsymbol{Q}} \sum_{k \in N_{i',j^*}} r_{i',j^*,k,l_1,l_2}$ to UE i' for the RBs on CC j^*
18: Re-allocate information bits on RBs in N_{i',j^*} and update $D_{i'}$ and $V(j^*,k)$ for all $k \in N_{i',j^*}$
19: **end for**
20: **until** $\boldsymbol{U} = \phi$ or $D_i = 0$ for all UE i

employ at most z CCs. The constraint in (5) ensures that all the information bits allocated to each UE i cannot exceed its traffic demand, i.e., queue size D_i (bits). In backlogged traffic, we assume that the queue size of each UE is infinite (i.e. $D_i \to \infty$) at every TTI. In contrast, in finite queue traffic, we assume that each UE has a finite queue size D_i. Due to space limitation, we have shown in our technical report [9] that the above scheduling problem is NP-hard. Therefore, we propose a 1/2-approximation greedy algorithm in the next section.

III. 1/2-Approximation Algorithm

In this section, we present a greedy scheme to find a sub-optimal solution of RRA. Due to space limitation, we prove that the proposed greedy has an approximation rate of 1/2 in [9]. To reduce the problem complexity, we decompose the RRA model into two subproblems: (i) CC-MCS allocation: assign CCs to UEs, and decide a suitable MCS for each TB of the assigned CCs (ii) RB-selection: base on the determined MCSs, allocate proper RBs of a CC to each UE, and assign the information bits to the RBs. We propose Algorithms 1 and 2 to solve the above two subproblems individually. The procedure of CC-MCS allocation, as shown in Algorithm 1, is summarized as follows.

1) Line 1: For each TTI, update the priority weight w_i for each UE i based on the average transmission rate served before TTI i, and update the queue size D_i for each UE i.

2) Lines 2-3: Let $\boldsymbol{U}$ be the set of candidate UE-CC assignments, which is initially set to $\boldsymbol{U} = \{(i,j) | i \in \boldsymbol{M}, j \in \boldsymbol{N}\}$. Let $V(j,k)$ denote the weighted transmission rate of the current assignment for RB k of CC j and be initialized to zero for all j and k.

3) Lines 5-8: Let $g(i,j,l_1,l_2)$ be the gain of weighted transmission rate of an assignment (i,j,l_1,l_2) over the rate of the current assignment, $V(j,k)$. An assignment with a higher gain indicates that a higher weighted transmission rate can be achieved by applying the new assignment. We will describe later how $g(i,j,l_1,l_2)$ is obtained in Algorithm 2. After calculating the gains of all possible assignments, i.e., all combinations of $\boldsymbol{U}$ and MCSs, we can find the best assignment (i^*, j^*, l_1^*, l_2^*) that returns the largest gain, and assign CC j^* with MCSs l_1^*, l_2^* to UE i^*.

4) Lines 9-10: While calculating $g(i,j,l_1,l_2)$ in step 2, Algorithm 2 at the same time allocates the RBs of CC j to UE i, which are collected as a set R_{i,j,l_1,l_2}. Therefore, once the assignment (i^*, j^*, l_1^*, l_2^*) is selected, the information bit allocation for assignment (i^*, j^*, l_1^*, l_2^*) is also determined by Algorithm 2. After allocating information bits to RBs in R_{i^*,j^*,l_1^*,l_2^*}, the value of $V(j^*,k)$ for all RBs k in R_{i^*,j^*,l_1^*,l_2^*} should be updated to the weight transmission rate of UE i, i.e., $V(j^*,k) = w_{i^*} r_{i^*,j^*,k,l_1^*,l_2^*}$. Finally, the bits allocated to R_{i^*,j^*,l_1^*,l_2^*} should be removed from D_{i^*}.

5) Lines 11-14: Remove the selected assignment (i^*, j^*) from $\boldsymbol{U}$ so that it will not be further considered. Moreover, if UE i^* has been assigned up to z CCs, all pairs in $\boldsymbol{U}$ corresponding to UE i^* are removed so that UE i^* will not be assigned any other CCs.

6) Lines 15-19: Note that, after steps 4-5, the RBs R_{i^*,j^*,l_1^*,l_2^*} assigned to UE i might originally be allocated to another UE i' in the previous iterations. If this is a case, since those UEs i' might use fewer RBs now, they could improve their rates by reselecting a better MCS for their remaining RBs, subject to the MCS constraint shown in Eq. (2). Therefore, for those i', we can update their MCSs to the one providing them the maximum rate by $(l_1', l_2') = \arg\max_{(l_1,l_2)\in\boldsymbol{Q}} \sum_{k \in N_{i',j^*}} r_{i',j^*,k,l_1,l_2}$, where N_{i',j^*} is the set of remaining RBs of CC j^* allocated to UE i'. The information bits for UE i' should also be re-allocated or returned back to the queue accordingly.

7) Lines 7,20: Repeat steps 3-6 until any of the following conditions is satisfied: (i) all UEs have decided which CCs to employ, i.e. all pairs are removed from $\boldsymbol{U}$, (ii) no assignment that can improve utilization efficiency of any RB of any CC can be found, i.e. $g(i^*, j^*, l_1^*, l_2^*) = 0$, and (iii) the queues of all UEs become empty.

We next describe how to allocate RBs as well as information bits using Algorithm 2. Given a CC-MCS assignment, (i,k,l_1,l_2), and the queue size of UE i, D_i, requested by Algorithm 1, Algorithm 2 selects a set of suitable RBs $R(i,j,l_1,l_2)$ in the assigned CC j and decide how to allocate information bits on RBs $R(i,j,l_1,l_2)$. Given the RBs and information bits allocation, Algorithm 2 also calculates the

Algorithm 2 Optimal RB Selection and Bit Allocation

1: Collect RBs with a positive gain in $R_{i,j,l_1,l_2} = \{k|k\in\boldsymbol{P}, w_i r_{i,j,k,l_1,l_2} > V(j,k)\}$
2: **if** $D_i \geq \sum_{k\in R_{i,j,l_1,l_2}i} r_{i,j,k,l_1,l_2}$ **then**
3: $\quad g(i,j,l_1,l_2) = \sum_{k\in R_{i,j,l_1,l_2}} w_i(r_{i,j,k,l_1,l_2} - V(j,k))$
4: $\quad$ Assign bits r_{i,j,k,l_1,l_2} to RB k for all $k\in R_{i,j,l_1,l_2}$
5: **else**
6: $\quad$ Sort RBs R_{i,j,l_1,l_2} in the ascending order of $V(j,k)$
7: $\quad g(i,j,l_1,l_2) = 0$
8: $\quad$ **for** $k = 1$ to $|R_{i,j,l_1,l_2}|$ **do**
9: $\quad\quad$ **if** $r_{i,j,k,l_1,l_2} * T < D_i$ **then**
10: $\quad\quad\quad g(i,j,l_1,l_2) = g(i,j,l_1,l_2) + w_i(r_{i,j,k,l_1,l_2} - V(j,k))$
11: $\quad\quad\quad D_i = D_i - r_{i,j,k,l_1,l_2} * T$
12: $\quad\quad\quad$ Assign bits $r_{i,j,k,l_1,l_2}T$ to RB k
13: $\quad\quad$ **else**
14: $\quad\quad\quad$ **if** $w_i D_i/T > V(j,k)$ **then**
15: $\quad\quad\quad\quad g(i,j,l_1,l_2) = g(i,j,l_1,l_2) + w_i(D_i - V(j,k))$
16: $\quad\quad\quad\quad$ Assign bits $D_i T$ to RB k
17: $\quad\quad\quad$ **end if**
18: $\quad\quad\quad$ Remove the unused RBs from R_{i,j,l_1,l_2}
19: $\quad\quad\quad$ **break**
20: $\quad\quad$ **end if**
21: $\quad$ **end for**
22: **end if**
23: **return** R_{i,j,l_1,l_2} and $g(i,j,l_1,l_2)$

gain of this assignment $g(i,j,l_1,l_2)$, which will be returned to Algorithm 1. Intuitively, while allocating the RBs of CC j to UE i, it is obvious that only the RBs which provide UE i a higher weighted transmission rate than the current assignment would be assigned. RRA hence compares $w_i r_{i,j,k,l_1,l_2}$ of each RB k with the weight rate of the current assignment, i.e., $V(j,k)$, and considers assignment (i,k,l_1,l_2) as a new assignment if $w_i r_{i,j,k,l_1,l_2} > V(j,k)$. However, since the RBs that can produce gains might provide a higher rate than the required traffic demand D_i, we might not need to allocate all such RBs to UE i. Algorithm 2 hence considers the traffic demand of UE i. The detailed procedure is as follows.

1) Line 1: The RBs j that satisfy $v(i,j,k,l_1,l_2) > V(j,k)$ could be added into an initial RB set R_{i,j,l_1,l_2}.

2) Lines 2-4: If D_i is infinite or is higher than the sum rate provided by R_{i,j,l_1,l_2}, assign all the RBs in R_{i,j,l_1,l_2} to UE i and compute the gain of allocating R_{i,j,l_1,l_2} by $g(i,j,l_1,l_2) = \sum_{k\in R_{i,j,l_1,l_2}} w_i(r_{i,j,k,l_1,l_2} - V(j,k))$.

3) Lines 6-7: Otherwise, we only need to assign a portion of the RBs in R_{i,j,l_1,l_2} to UE i. However, since the weight transmission rate of each RB, $V(j,k)$, could be different, we sort the RBs in R_{i,j,l_1,l_2} in the descending order of gains $r_{i,j,k,l_1,l_2} - V(j,k)$ and give the RBs with a higher gain a higher priority to be selected. We also initialize the gain to zero.

4) Lines 9-12: The algorithm then keeps allocating the RB with the highest priority to UE i, removes the allocated bits from the traffic demand D_i, and increases the gain by $w_i(r_{i,j,k,l_1,l_2} - V(j,k))$. The iterative procedure stops until the remanding demand cannot fully use the whole RB.

5) Lines 14-19: If UE i's remaining traffic demand cannot fully utilize the resources in RB k, it is uncertain whether allocating the remaining demand D_i to RB k can produce a positive gain. Therefore, we should only assign the remaining bits to RB k if $w_i D_i/T > V(j,k)$. In addition, we do not need to consider the following RBs, and can remove those unused RBs from R_{i,j,l_1,l_2} and terminate the algorithm.

6) Line 23: The algorithm finally returns the allocated RBs R_{i,j,l_1,l_2} and gain $g(i,j,l_1,l_2)$ to Algorithm 1.

The total complexity of this algorithm is $O(|\boldsymbol{M}|^2 z|\boldsymbol{N}||\boldsymbol{Q}||\boldsymbol{P}|\log|\boldsymbol{P})|$. However, Algorithm 1 can be further improved by following simplifications: (i) After all possible gains are calculated, those candidate assignments with the zero gain can be removed; (ii) After all the possible gains being calculated in the first iteration, the algorithm only needs to update the gains of the assigned CC in the following iterations, because each iteration may only change the RB selection of an assigned CC. The gains of other CCs that are already used in the previous iteration do not need to be re-calculated. Therefore, the total complexity can be reduced to $O(|\boldsymbol{M}||\boldsymbol{N}||\boldsymbol{Q}||\boldsymbol{P}|\log|\boldsymbol{P}| + |\boldsymbol{M}||\boldsymbol{Q}||\boldsymbol{P}|\log|\boldsymbol{P}|(z|\boldsymbol{M}| - 1)) = O(|\boldsymbol{M}||\boldsymbol{Q}||\boldsymbol{P}|\log|\boldsymbol{P}|(|\boldsymbol{N}| + z|\boldsymbol{M}| - 1)$.

IV. Simulation Results

We adopt the LTE-EPC network simulator [10] with the CA module to simulate LTE-A network scenarios and evaluate the performance of our proposed scheme. This network simulator enhances the LTE-related modules on the ns-3 network simulator [11]. Two possible CA scenarios *S1* and *S2* are evaluated. Both scenarios are deployed with four downlink (DL) CCs of 5MHz bandwidth. In *S1*, four CCs are at 2GHz frequency band; in *S2*, those are at 800MHz, 800MHz, 2GHz, and 2GHz frequency band, respectively. *S1* represents the scenarios where all the CCs are at the higher frequency band, while *S2* represents the scenarios where some of the CCs are at higher frequency band but some are at the lower frequency band, which can provide a wider coverage. The number of LTE-A UEs varies from 10 to 50, and UEs are uniformly-distributed in a cell and has a mobility velocity varying from 1 mps to 15 mps. Each UE can use up to two CCs simultaneously, and is configured as one of three MIMO modes: SISO, transmit diversity and spatial multiplexing. We consider both the Backlogged traffic and finite queue traffic models. Each simulation scenario lasts 10 seconds (i.e., 10,000 TTIs), and is repeated 50 times for reporting the average result. Table I summaries other parameters used in the simulations.

We compare the performance of our scheme, called *MIMO-RRA* with two schemes proposed in [6] and [7], respectively. However, the scheme in [6] does not involve CC assignment, which could generally be performed using the Least Load (*LL*) approach [12]. Therefore, we integrate the

TABLE I
SIMULATION SETTINGS

Parameter	Setting
Inter-site distance (ISD)	500 m
Number of antennas of each UE	2x2
Number of RBs per CC	25 (12 subcarriers per RB)
Path loss	$L = I + 37.6 \log_{10}(R)$, R in km $I = 128.1$ (2GHz), $I = 120.9$ (900 MHz) [13]
Penetration loss	20dB
Shadowing loss	Gaussian distribution with zero mean and standard deviation 8dB
Multipath	Jakes' model [14]
Available MCSs	29 possible MCSs are available as defined in 3GPP TS 36.213 [2]
TTI (Subframe)	1 ms
Granularity of CSI feedback	100 TTIs
Granularity of scheduling	1 TTI

Least Load approach with the MIMO scheme proposed in [6], called *MIMO-LLPS* hereafter. Second, the scheme proposed in [7], called *SISO-RRA*, solves the resource allocation problem with consideration of CC assignment, but only consider the SISO mode.

A. Results for Backlogged Traffic

We first evaluate the performance of comparison schemes in terms of the mean cell throughput and the degree of fairness for backlogged traffic in three UE deployment scenarios with different numbers of UEs. Fig. 2 plots the mean cell throughput, which is defined as the total throughput of all UEs after averaging across all simulations. The figure shows that our scheme increases the mean cell throughput by about 45.8% in *S1* and 47.8% in *S2*, as compared to *SISO-RRA*. The gain is from allowing UEs to exploit multiple antennas to use a higher MCS and more TBs. As compared to *MIMO-LLPS*, our scheme improves the mean cell throughput by about 20.9% in *S1* and 13.2% in *S2*. The improvement comes from two reasons: (i) the proper assignment of CCs to UEs at each TTI with consideration of heterogeneous channel quality of different CCs; the phenomenon is especially obvious in *S2* where channel conditions of different CCs differ, and (ii) our scheme reassigns the higher-rate MCSs to UEs on a CC based on up-to-date assignment of CCs, while *MIMO-LLPS* only assigns MCSs to UEs in the initial stage without adapting to the updated resource allocation.

While applying a scheme to different numbers of UEs, the mean cell throughput is slightly changed due the following reasons: (i) More UEs result in a higher probability of assigning RBs to the UEs with a better channel quality, which increases the mean cell throughput; (ii) on the contrary, to maintain fairness, RRA should reduce the number of RBs assigned to each UE, which leads to a lower mean cell throughput. Due to the above two conflict reasons, the mean cell throughput may vary slightly with different numbers of UEs. In addition, the CCs with higher frequency (2 GHz) would suffer from larger path loss than those with lower frequency (800 MHz).

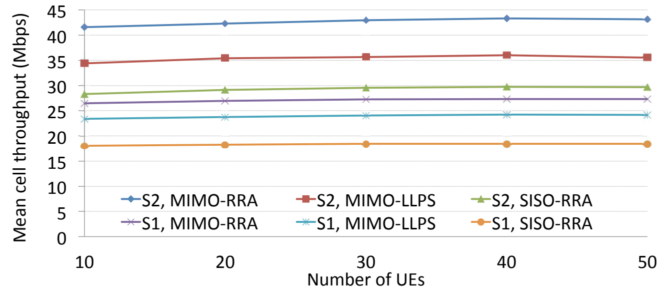

Fig. 2. Mean cell throughput vs. numbers of UEs.

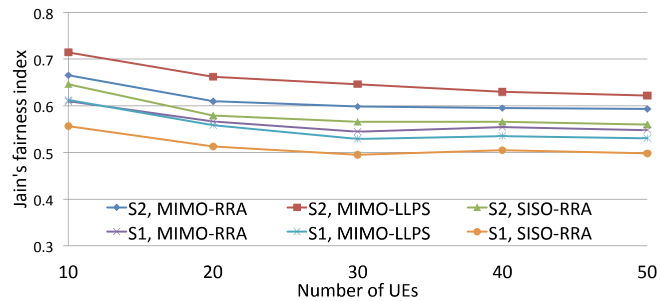

Fig. 3. Jain's fairness index vs. number of UEs.

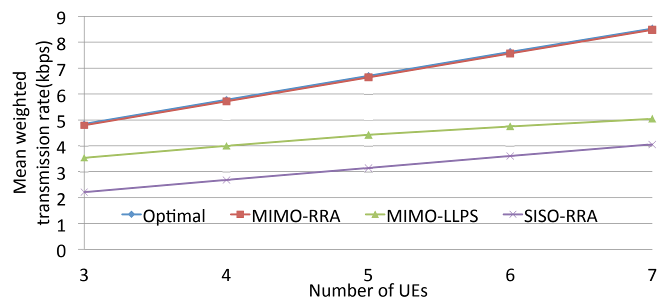

Fig. 4. Mean weighted transmission rate vs. number of UEs.

Therefore, more UEs with a higher channel quality are in *S2* than in *S1* such that the throughput in *S2* is generally higher than that in *S1*.

Fig. 3 shows the degree of fairness F among all UEs , which is analysed by Jain's fairness index [15], i.e., $F = (\sum_{i=1}^{m} \mu_i)^2 / m \sum_{i=1}^{m} \mu_i^2$ where μ_i is the average transmission rate of UE i. The value of F ranges from $1/m$ to 1, and $F = 1$ represents that all UEs have an equal average transmission rate. The results show that the degree of fairness of our scheme in *S2* is sacrificed slightly because of its higher improvement in the mean cell throughput. Specifically, our scheme takes the channel quality of CCs into consideration, and selects the suitable UEs for RBs to increase the throughput. Therefore, the degree of fairness would be worsen in the scenarios where the channel quality of CCs varies.

Finally, we compare our scheme with the optimal solution, which is found using exhausted search. Such comparison is only performed in small-scale scenarios due to the expensive computational complexity. The scenario consists of two DL CCs of 1.4 MHz at 2GHz frequency band. The performance

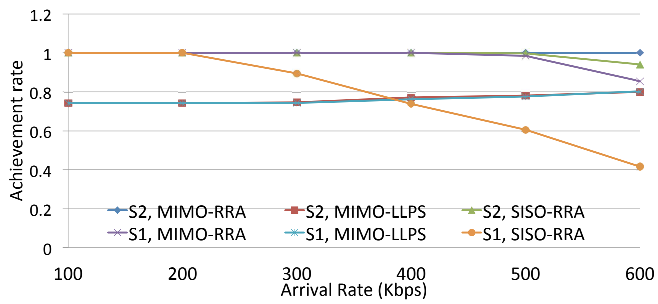

Fig. 5. Achievement rate vs. data arrival rate.

is evaluated by the mean weighted transmission rate, indicating that the weighted transmission rate of all UEs in the cell is summarized and averaged across all simulations. The mean weighted transmission rate for different schemes with various numbers of UEs is shown in Fig. 4. The results show that our solution is fairly close to the optimal solution under the small-scale scenarios.

B. Results of Finite Queue Traffic

Since the amount of transmitted data depends on the amount of data in the queue of each UE at each TTI, we evaluate the performance of the schemes by the following equation: $Achievement\, rate = transmitted\, bits(t)/data\, demand(t)$. The achievement rate indicates the percentage of data in the queue of a UE that are transmitted. The achievement rate ranges from 0 to 1, while $Achievement\, rate = 1$ represents that all the data in the queue of a UE can be transmitted in this TTI. We define the data queue size as 500k bits, and measure the achievement rate for simulations with different data arrival rates, ranging from 100 to 600 (kbps), in the three comparison schemes.

The achievement rate for different schemes with various arrival rates is shown in Fig. 5. The achievement rate of our scheme is quite close to 1 in each scenario, while the achievement rate of *MIMO-LLPS* is about 0.76. The achievement rate of *SISO-RRA* is close to 1 when the arrival rate is less than 200kbps, but dramatically decreases as the arrival rate increases. This is caused by bandwidth limitation such that the available bandwidth resources of the SISO mode cannot afford such heavy arrival data.

V. Conclusion

In this paper, we have investigated the downlink radio resource allocation problem for carrier-aggregation based MIMO LTE-A systems. We formulate the resource allocation problem as an optimization model with consideration of the MCS constraint specified in LTE-A standards and two traffic models, i.e., backlogged traffic and finite queue model. Due to its NP-hardness, we therefore propose a 1/2-approximation algorithm to find the suboptimal solution of maximizing the system throughput, while maintaining proportional fairness among UEs. Our simulation results show that the proposed algorithm outperforms the existing schemes that do not consider either carrier aggregation or MIMO capability.

References

[1] “Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2,” 3rd Generation Partnership Project (3GPP), TS 36.300, Jun. 2012.

[2] “Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures,” 3rd Generation Partnership Project (3GPP), TS 36.213, Jun. 2012.

[3] Y. Wang, K. I. Pedersen, T. B. Sorensen, and P. E. Mogensen, “Utility Maximization in LTE-Advanced Systems with Carrier Aggregation,” in *Vehicular Technology Conference (VTC Spring), 2011 IEEE*, May 2011, pp. 1–5.

[4] S.-B. Lee, S. Choudhury, A. Khoshnevis, S. Xu, and S. Lu, “Downlink MIMO with Frequency-Domain Packet Scheduling for 3GPP LTE,” in *INFOCOM 2009, IEEE*, Apr. 2009, pp. 1269–1277.

[5] “Feasibility study for Further Advancements for E-UTRA (LTE-Advanced),” 3rd Generation Partnership Project (3GPP), TR 36.912, Mar. 2011.

[6] S. R. Honghai Zhang, Narayan Prasad, “MIMO Downlink Scheduling in LTE Systems,” in *INFOCOM 2012 Proceedings, IEEE*, March 2012, p. 2936V2940.

[7] H. S. Liao, P. Y. Chen, and W. T. Chen, “An Efficient Downlink Radio Resource Allocation with Carrier Aggregation in LTE-Advanced Networks,” Department of Computer Science, National Tsing Hua University, Hsin-Chu, 300, Taiwan, Tech. Rep., 2012.

[8] A. Jalali, R. Padovani, and R. Pankaj, “Data Throughput of CDMA-HDR a High Efficiency-High Data Rate Personal Communication Wireless System,” in *Vehicular Technology Conference (VTC Spring), 2000 IEEE*, vol. 3, 2000, pp. 1854–1858.

[9] P. L. Tsai, Kate C. J. Lin, and W. T. Chen, “Downlink Radio Resource Allocation with Carrier Aggregation and MIMO in LTE-Advanced Networks,” Department of Computer Science, National Tsing Hua University, Tech. Rep., 2013. [Online]. Available: http://mnet.cs.nthu.edu.tw/publication/100062572/LTE_CA_MIMO_RRA.pdf

[10] “LTE-EPC Network Simulator (LENA) - Iptechwiki.” [Online]. Available: http://iptechwiki.cttc.es/LTE-EPC_Network_Simulator_(LENA)

[11] “ns-3 network simulator.” [Online]. Available: http://www.nsnam.org/

[12] T. Dean and P. Fleming, “Trunking Efficiency in Multi-Carrier CDMA Systems,” in *Vehicular Technology Conference (VTC Fall), 2002 IEEE*, vol. 1, 2002, pp. 156–160.

[13] “Physical layer aspects for evolved Universal Terrestrial Radio Access (UTRA),” 3rd Generation Partnership Project (3GPP), TR 25.814, Sep. 2006.

[14] W. C. Jakes, *Microwave Mobile Communications*. New York: John Wiley & Sons Inc., Feb. 1975.

[15] R. Jain, D. M. Chiu, and W. Hawe, “A Quantitative Measure of Fairness and Discrimination for Resource Allocation in Shared Computer System,” DEC, TR 301, Sep. 1984.