LTE-A Downlink Resource Management for Green Communication

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***Abstract*—LTE-A adopts carrier aggregation to support high-speed transmission by integrating component carriers to send data to a single user. While many resource scheduling schemes seek to maximize network throughput, the paper aims at providing green communication for LTE-A. Specifically, we define an *energy-reduction LTE-A resource management (ELRM) problem* to allocate downlink resource to user devices by carrier aggregation, such that the energy expense of LTE-A network is minimized, under the constraint that user demands are satisfied. ELRM is NP-hard, so we develop an energy-efficient heuristic by considering the channel quality, data backlog, and energy consumption of each device. Simulation results show that our ELRM solution significantly saves the energy consumption of user devices and base station, thereby achieving green communication.**

***Index Terms*—carrier aggregation, downlink resource scheduling, energy efficient, green communication, LTE-A.**

I. INTRODUCTION

To provide high-speed wireless access and meet the 4G requirement [1], 3GPP defines the specification of *long term evolution–advanced (LTE-A)* which provides the maximum channel bandwidth of 100MHz. Unfortunately, a lot of bands in the communication spectrum have been occupied by 2G and 3G systems. To deal with this problem, LTE-A applies the *carrier aggregation (CA)* technique to combine frequency segments, namely *component carriers (CCs)*, to acquire wider bandwidth. For instance, the base station (BS) can integrate five 20MHz CCs to get 100MHz bandwidth. The CA technique is backward-compatible with previous LTE *user equipments (UEs)*. Moreover, the BS is allowed to combine CCs in different bands to increase the channel utilization [2].

CA can well enhance LTE-A throughput but it is a challenge to allocate downlink resource to each UE. According to [3], most existing methods are categorized into two groups: *CC selection* and *resource block (RB) assignment*. CC selection considers how to designate the usage of each CC, whereas RB assignment determines how to distribute RBs (i.e., the basic resource unit in a CC) among UEs for transmission. Numerous methods try to improve overall throughput by, for example, increasing the channel quality of UEs or balancing the traffic loads among CCs. However, the issue of saving energy on data transmission is rarely discussed. When receiving data from noncontiguous CCs, a UE has to activate multiple hardware components such as radio-frequency chain and fast Fourier transform modules. This phenomenon apparently spends more energy of the UE. Also, the BS should transmit in more power on each CC to improve its channel quality. The above situation will inevitably result in energy wastage and interference to neighboring cells.

Therefore, our paper formulates an *energy-reduction LTE-A resource management (ELRM)* problem. It addresses how to select CCs and allocate RBs to each UE such that the energy consumption of UEs and the transmission power of BS can be minimized, under the constraints that 1) the sum of power on every CC does not exceed the BS's capacity, 2) the traffic demand of each UE is satisfied. The ELRM problem is NP-hard, so we propose an energy-efficient heuristic. The basic concept is to find a suitable *modulation and coding scheme (MCS)* for every pair of CC and UE according to an initial power assumption. Then, we iteratively select a CC to satisfy the demand of each UE by considering multiple parameters, including channel quality, data backlog, and energy expense. Finally, we degrade the power on some CCs if feasible. Through simulation, the results verify that the proposed ELRM solution can significantly reduce the energy expense on data transmission, which demonstrates that it can support green communication for LTE-A.

We organize the remaining part of this paper below. The next section presents related work. Section III formulates the ELRM problem, and we propose our solution in Section IV. Then, Section V gives the simulation study. Finally, we conclude this paper and discuss some future work in Section VI.

II. RELATED WORK

For CC selection, many static solutions have been developed. The *random* solution [4] picks available CCs for UEs to provide balanced load. The *least-load* solution [5] selects the CC with minimum load to transmit packets. The *circular* solution [6] designates CCs to UEs in a round-robin fashion. However, they do not consider the change of network situation and may thus hurt throughput. Consequently, several studies dynamically assign CCs based on the channel quality of UEs. For example, [7] adopts a geometry factor to find the UEs that are close to cell edge, and then assigns low-frequency, robust CCs to improve their throughput. In [8], the CCs with similar condition are grouped together to increase spectrum utilization. It then develops a utility-based selection scheme by taking channel quality and load balance into account. The work of [9] solves the CC selection problem through an economic model, where the data rate of each CC is viewed as a sale item and the UE experience is treated as profit. Then, CCs are scored by the states of utilization with the objective of maximizing total profit. Nevertheless, these studies do not consider reducing energy consumption on data communication.

For RB assignment, numerous solutions without CA have been proposed. The study of [10] employs a utility function to calculate the user's satisfaction degree on each flow, and allows flows to compete for RBs accordingly. The work of [11] formulates an optimization problem for RB assignment to maximize throughput, and finds the suboptimal solution with the help of a meta-heuristic. In [12], flows are divided into urgent and non-urgent groups, where urgent flows are given with a higher priority for transmission first. The study of [13] assigns RBs to flows by their channel quality, and asks non-urgent flows to return some RBs. Such RBs are then given to the flows threatened by packet dropping. The work of [14] uses a virtual queue to predict the incoming of future packets, and drops those packets that cannot meet their deadlines.

Several RB assignment methods with CA are also developed. The work of [15] uses a backlog-based strategy to assign RBs, where the backlog of a UE is the amount of its unsatisfied demand. Then, the UEs with larger backlog can obtain RBs first. Inspired by proportional fairness [16], [17], Guan et al. [18] give a high priority to the UEs that have better channel quality or encounter worse channel condition in the past, as so to take care of both throughput and fairness. The study of [19] defines an RB assignment problem with the MCS constraint, where only one MCS is allowed for each assigned CC across all of its assigned RBs for a UE. Then, a greedy-based method is developed by assigning each RB to the UE with the highest rate. Obviously, these methods aim at increasing throughput or keeping fairness. However, none of them support green communication for LTE-A. This distinguishes this paper from the above studies.

III. ELRM Problem Definition

ELRM aims at one LTE-A cell managed by a BS with the maximum transmission power $P^{\mathrm{BS}}_{\max}$. There is a set $\hat{U}$ of UEs in the cell, where each $u_i \in \hat{U}$ has downlink transmission request of r_i. Besides, the spectrum is cut into a set $\hat{C}$ of CCs, and the BS is allowed to adjust the transmission power P^{CC}_j on each $c_j \in \hat{C}$. Based on its bandwidth, each CC c_j can provide b_j RBs. With CA, a UE can obtain RBs from different CCs, but it can listen to no more than α CCs (specifically, $\alpha = 5$ according to the LTE-A standard [20]).

Let $d^{m(i,j)}_{j,k}$ denote the number of bits transmitted by the kth RB of CC c_j with MCS $m(i,j)$ for a UE u_i. We also define a variable $\beta(i,j,k)$ to indicate whether the kth RB of c_j is allocated to u_i, where $\beta(i,j,k) = 1$ if so, or $\beta(i,j,k) = 0$ otherwise. Then, ELRM asks how to allocate RBs to UEs, and set MCS and power for each CC, such that

$$\min \sum\nolimits_{u_i \in \hat{U}} P^{\mathrm{UE}}_i, \tag{1}$$

$$\min \sum\nolimits_{c_j \in \hat{C}} P^{\mathrm{CC}}_j, \tag{2}$$

under two constraints:

$$\sum\nolimits_{c_j \in \hat{C}} P^{\mathrm{CC}}_j \leq P^{\mathrm{BS}}_{\max}, \tag{3}$$

$$\sum\nolimits_{j,k} d^{m(i,j)}_{j,k} \times \beta(i,j,k) \geq r_i t, \tag{4}$$

where P^{CC}_j denotes the overall power required by u_i to receive data from its assigned CCs, and t is the length of a scheduling period. Here, Eq. (1) reduces the energy expense of UEs on receiving data, while Eq. (2) saves the BS's power on sending data. These two equations together provide green communication. Moreover, Eq. (3) means that the sum of power on each CC cannot exceed the BS's capacity, and Eq. (4) indicates that the demand of each UE should be satisfied. To calculate the value of P^{CC}_j, we adopt the energy consumption model in [21] as follows:

$$\text{[Contiguous CA] } P^{\mathrm{CC}}_j = \tilde{P}_{\mathrm{Rx}} + \tilde{P}_{\mathrm{RF}}(S_{\mathrm{Rx}}) + \tilde{P}_{\mathrm{BB}_1}(R_{\mathrm{Rx}_1}) + \tilde{P}_{\mathrm{BB}_2}(R_{\mathrm{Rx}_2}) + \tilde{P}_{\mathrm{AC}}(\mathrm{W}) + \tilde{P}_{\mathrm{CW}} \times (\rho_{\mathrm{CW,cc}_1} + \rho_{\mathrm{CW,cc}_2}), \tag{5}$$

$$\text{[Noncontiguous CA] } P^{\mathrm{CC}}_j = 2\tilde{P}_{\mathrm{Rx}} + \tilde{P}_{\mathrm{RF}_1}(S_{\mathrm{Rx}_1}) + \tilde{P}_{\mathrm{RF}_2}(S_{\mathrm{Rx}_2}) + \tilde{P}_{\mathrm{BB}_1}(R_{\mathrm{Rx}_1}) + \tilde{P}_{\mathrm{BB}_2}(R_{\mathrm{Rx}_2}) + \tilde{P}_{\mathrm{AC}_1}(\mathrm{W}_1) + \tilde{P}_{\mathrm{AC}_2}(\mathrm{W}_2) + \tilde{P}_{\mathrm{CW}} \times (\rho_{\mathrm{CW,cc}_1} + \rho_{\mathrm{CW,cc}_2}), \tag{6}$$

where $\tilde{P}_{\mathrm{Rx}}$ is the power used to activate the receive chain (denoted by 'Rx'), $\tilde{P}_{\mathrm{RF}}(S_{\mathrm{Rx}})$ is the power spent by radio frequency with power level S_{Rx}, $\tilde{P}_{\mathrm{BB}}(R_{\mathrm{Rx}})$ is the power consumed by baseband with data rate R_{Rx}, $\tilde{P}_{\mathrm{AC}}(\mathrm{W})$ is the power taken by analog-to-digital converter with bandwidth W, $\tilde{P}_{\mathrm{CW}}$ is the power spent by two codewords, and ρ_{CW} is the probability of using two codewords.

Theorem 1: The ELRM problem is NP-hard.

Proof: A *frequency-domain packet scheduling (FDPS) problem* is shown as NP-hard in [22]. It asks how to allocate RBs and select one of two MIMO modes to each UE to maximize throughput. FDPS has two constraints. First, each RB is allocated to only one UE. Second, only one MIMO mode is chosen for all assigned RBs of a UE.

We prove that ELRM is NP-hard by showing that FDPS is a special case of ELRM. Specifically, since FDPS considers LTE Release 8/9 systems without CA, we formulate an ELRM problem instance that considers an LTE-A network with just one CC and two MCSs. In this way, the choice between these two MCSs in ELRM will be equivalent to the choice between the two MIMO modes in FDPS. It thus verifies that the ELRM problem instance is equivalent to the FDPS problem. Actually, ELRM allows more than two MCSs and also CA. This implies that ELRM is more difficult than FDPS. Therefore, the ELRM problem must be also NP-hard. ■

IV. The Proposed Solution

In each scheduling period, the LTE-A BS executes our ELRM solution to allocate downlink resource to UEs, which consists of seven steps.

STEP 1: We set the initial power on every CC $c_j \in \hat{C}$ to meet the constraint in Eq. (3). One simple way is to set

TABLE I: CQI table defined in LTE-A [20].

CQI index	MCS	code rate (× 1024)	efficiency	bits per RB ($d_{j,k}^{m(i,j)}$)
1	QPSK	78	0.1523	12.79
2	QPSK	120	0.2344	19.69
3	QPSK	193	0.3770	31.67
4	QPSK	308	0.6016	50.53
5	QPSK	449	0.8770	73.67
6	QPSK	602	1.1758	98.77
7	16QAM	378	1.4766	124.03
8	16QAM	490	1.9141	160.78
9	16QAM	616	2.4063	202.13
10	64QAM	466	2.7305	229.36
11	64QAM	567	3.3223	279.07
12	64QAM	666	3.9023	327.79
13	64QAM	772	4.5234	379.97
14	64QAM	873	5.1152	429.68
15	64QAM	948	5.5547	466.59

$P_j^{\mathrm{CC}} = P_{\max}^{\mathrm{BS}}/n$, where n is the total number of available CCs in $\hat{C}$.

STEP 2: Based on the initial power, the BS broadcasts a downlink reference signal to all UEs in the cell. Thus, each UE can evaluate its channel condition, which is done by estimating the SINR ratio on each CC and finding the largest CQI (channel quality indicator) such that the error rate does not exceed a threshold γ (e.g., $\gamma \leq 0.1$). Then, the UE can notify the BS of its CQI for reference.

STEP 3: With CQI notification, the BS can find a suitable MCS for every pair of UE and CC. From Table I, we know how many bits can be transmitted by one RB with different MCS. So, the BS calculates a *bit-rate reference table* $\mathcal{T}_{ref}$ according to the information in Table I. Each tuple (u_i, c_j) stores the number of bits sent by CC c_j for UE u_i, whose value is $\mathcal{V}(u_i, c_j) = d_{j,k}^{m(i,j)} \times b_j$, where the BS assigns MCS $m(i,j)$ to c_j, and c_j has b_j RBs.

STEP 4: Then, we employ a variable Q_i to record the *backlog* of each $u_i \in \hat{U}$, which indicates how many bits are not transmitted yet for u_i. Then, UEs are decreasingly sorted according to their Q_i values.

STEP 5: We iteratively pick the UE u_i with the largest Q_i value for scheduling. The BS then assigns one CC to u_i based on the CC's weight and Q_i. Specifically, the weight of a CC c_j (for u_i) is defined by

$$w_j^i = \sum\nolimits_{\forall u_a \in \{\hat{U} - u_i\}, Q_a > 0} \mathcal{V}(u_a, c_j). \qquad (7)$$

From Eq. (7), the weight is actually the sum of bits supported by c_j for all UEs (except u_i) with positive backlog. A larger weight means that other UEs have good channel quality on c_j, so it is better to reserve c_j for later use. Then, two cases are considered. In the first case, no single CC can satisfy Q_i. Thus, we select the CC c_j with maximum $\mathcal{V}(u_i, c_j)$ value for u_i. When there is a tie, we select the CC with smallest weight. Then, we update u_i's backlog by $Q_i = Q_i - \mathcal{V}(u_i, c_j)$, and clear $\mathcal{V}(u_a, c_j)$, $\forall a$ to zero in $\mathcal{T}_{ref}$. In the second case, some CCs each can satisfy Q_i. Thus, we select the CC c_j with minimum weight, allocate a number of $\left\lceil Q_i / d_{j,k}^{m(i,j)} \right\rceil$ of c_j's RBs to u_i, and update $\mathcal{V}(u_a, c_j)$ in $\mathcal{T}_{ref}$ accordingly.

TABLE II: Example of the bit-rate reference table, where each number in parenthesis means the CQI index.

UE	c_1	c_2	c_3	c_4	c_5
u_1	(3) 380	(5) 884	(1) 153	(3) 380	(3) 380
u_2	(2) 236	(3) 380	(1) 153	(5) 884	(1) 153
u_3	(3) 380	(4) 606	(4) 606	(2) 236	(4) 606

STEP 6: The above step is repeated until either of the two situations occurs: 1) the demand of all UEs have been satisfied, and 2) the BS has no CC with a positive $\mathcal{V}(u_i, c_j)$ value but some UEs still have $Q_i > 0$. For case 1, we can execute the next step to further reduce the transmission power on some CCs. On the other hand, case 2 means that the BS has no sufficient resource to serve all UEs in $\hat{U}$, and thus the algorithm will terminate.

STEP 7: We check whether some CCs can be given with smaller power to meet UEs' demands. Suppose that a CC c_j is assigned to a UE u_i with MCS $m(i,j)$. Then, we try a new MCS $m'(i,j) < m(i,j)$ and check if c_j has enough RBs to satisfy u_i's demand. If so, we can lower down the power on c_j such that the MCS becomes $m'(i,j)$.

We present an example with three UEs and five CCs, where $b_j = 12$ for each CC and Table II shows the bit-rate reference table $\mathcal{T}_{ref}$ computed from Table I. Suppose that $Q_1 = 1150$, $Q_2 = 550$, and $Q_3 = 1200$ in the beginning. Then, our ELRM solution has the following iterations.

ITERATION 1: We first pick u_3 for scheduling, and c_2, c_3, and c_5 will be candidates. Since $w_2^3 = 1264$, $w_3^3 = 306$, and $w_5^3 = 533$, we assign c_3 to u_3, and set $\mathcal{V}(u_i, c_3) = 0$, for $i = 1..3$. Thus, $Q_3 = 1200 - 606 = 594$.

ITERATION 2: We then pick u_1 for scheduling, and c_2 will be the only candidate. Thus, we set $\mathcal{V}(u_i, c_2) = 0$, for $i = 1..3$, and update Q_1 by $1150 - 884 = 266$.

ITERATION 3: Then, u_3 is picked again for scheduling, and c_5 is the candidate. In this case, we assign c_5 to u_3, clear all $\mathcal{V}(u_i, c_5)$ to zero in $\mathcal{T}_{ref}$, and set $Q_3 = 0$.

ITERATION 4: We then assign c_4 to u_2. Here, since it requires only $\lceil 550/73.67 \rceil = 8$ RBs, we will have $\mathcal{V}(u_1, c_4) = \lfloor 31.67 \times (12 - 8) \rfloor = 126$, $\mathcal{V}(u_2, c_4) = \lfloor 73.67 \times (12 - 8) \rfloor = 294$, and $\mathcal{V}(u_3, c_4) = \lfloor 19.69 \times (12 - 8) \rfloor = 78$.

ITERATION 5: We finally assign c_1 to u_1. Therefore, u_1, u_2, and u_3 are eventually assigned with $\{c_1, c_2\}$, $\{c_4\}$, and $\{c_3, c_5\}$, respectively. Here, we can degrade MCS $m(2,4) = 5$ to the new MCS $m'(2,4) = 4$, because we have $d_{4,k}^{m'(2,4)} \times b_4 = 50.53 \times 12 > Q_2 = 550$.

We remark that many greedy-based methods try to pick the UE u_i with maximum demand and assign the best CC c_j to it. However, other UEs may also thirst for c_j, because they have good channel quality on c_j. Once c_j is assigned to u_i, other UEs may have to use CCs with bad channel quality. In this case, the BS has to aggregate more CCs to satisfy their demand, thereby not only wasting spectrum resource but also making UEs spend more energy. To deal with this problem,

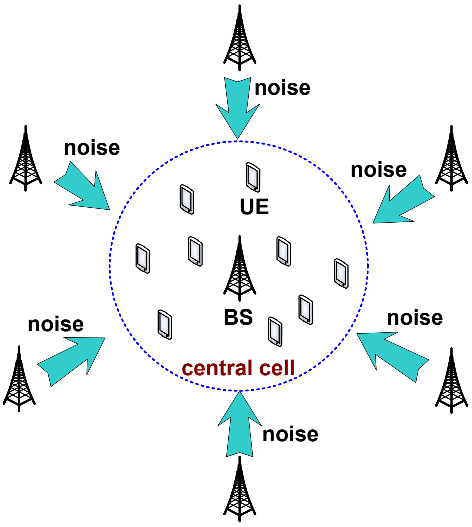


Fig. 1: Seven-cell deployment in our simulations, where we aim at the scheduling result of central cell.

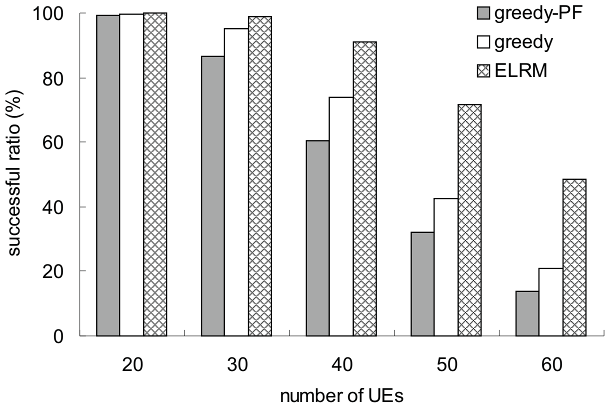
our ELRM solution adopts a CC weight in STEP 5. When the selected UE u_i has multiple choices of CCs, we can select the CC c_j with minimum weight, where other UEs do not have good channel quality on c_j. Through this way, assigning c_j to u_i can have less impact on other UEs whose demands have not been satisfied yet.

V. SIMULATION STUDY

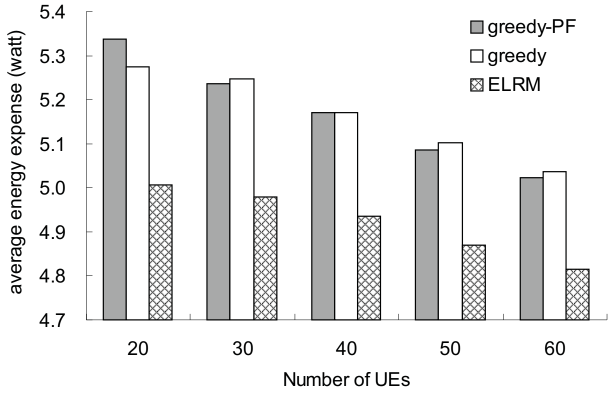
To measure system performance, we develop a simulator in C++ that considers seven-cell deployment in Fig. 1. Specifically, we aim at the scheduling result of central cell, and BSs in other cells will generate noise on different CCs. Besides, we use the log-distance model, $PL = 128.1 + 37.6 \log \hat{D}(\mathrm{BS}, u_i)$, to simulate the wireless signal propagation, where PL is the path loss and $\hat{D}(\mathrm{BS}, u_i)$ denotes the distance between the BS and a UE.

Our simulations consider both Band 1 (2110$\sim$2170MHz) and Band 5 (869$\sim$894 MHz), where Band 1 is divided into twelve 5MHz CCs, and Band 5 is divided into two 5MHz CCs and five 3MHz CCs. So, we have 19 available CCs. In the central cell, there are 20$\sim$60 UEs roaming, each with 50Mbps real-time traffic and 35Mbps non-real-time traffic. Besides, we set $P^{\mathrm{BS}}_{\max} = 40$watts.

Two LTE-A scheduling methods are used for comparison. The *greedy method with proportional fairness (greedy-PF)* [19] computes the weighted data rate of each UE on the RBs in every CC. Then, it iteratively selects the pair of UE and CC that has the maximum rate. To maintain fairness among UEs, a larger weight is given to a UE which sent less data in the past. Besides, we modify the greedy-PF method by setting all weights to one (so the effect of proportional fairness is eliminated) and call this method *the greedy method*. For each experiment, we repeat 1000 simulations and take their average.



(a) successful ratio of resource scheduling



(b) average energy expense of UEs

UEs	20	30	40	50	60
ratio	78.3%	66.1%	57.8%	51.4%	45.2%

(c) saving ratio of the BS's transmission power by ELRM

Fig. 2: Simulation results.

Fig. 2(a) gives the successful ratio of resource scheduling by different methods, which is defined by the ratio of the number of simulations that the BS can satisfy the demands of all UEs to the total 1000 simulations. Obviously, when there are more UEs, the successful ratio decreases because more UEs compete for the fixed spectrum resource. Since the greedy-PF method has the fairness concern, it may not allocate more resource to those UEs that currently enjoy good channel quality, thereby decreasing the successful ratio. By taking into consideration the factors of backlog, channel quality, and CC weight, our ELRM solution always has the highest ratio. Even though there are 60 UEs in the central cell, the ELRM solution still can keep around 50% of the successful ratio.

Fig. 2(b) illustrates the average energy expense of UEs on receiving data. When there are more UEs in the cell, each single UE would be allocated with less resource. In this case, each UE does not require much energy to use its resource accordingly. That is why the energy consumption decreases when the number of UEs grows. Both the greedy-PF and greedy methods let UE consume more energy, as they do not address energy expense in communication. On the contrary, our ELRM solution uses the technique of CC weight to reduce the number of aggregated CCs, thereby significantly saving energy consumption of UEs.

Fig. 2(c) shows the saving ratio of BS's transmission power by ELRM (comparing with both greedy-PF and greedy methods). Because the greedy-PF and greedy methods do not consider reducing the BS's energy consumption, they always ask the BS to emit the maximum transmission power. On the other hand, our ELRM solution seeks to decrease the transmission power on each assigned CC by using a lower MCS when possible. Thus, without losing system performance, it can reduce the BS's transmission power. We remark that when there are more UEs, the BS has to improve the channel quality of each CC to satisfy the growing demand. In this case, the saving ratio of BS's transmission power decreases, as the number of UEs increases.

VI. CONCLUSION AND FUTURE WORK

This paper formulates an ELRM problem by considering energy expense on communication when the CA technique is adopted in LTE-A networks. We show that ELRM is NP-hard and propose an energy-efficient solution by introducing the concept of CC weight. Moreover, our solution attempts to use a lower MCS for some CCs if feasible in order to decrease the overall transmission power. Through simulations, we demonstrate that our ELRM solution can increase the successful ratio of resource scheduling, reduce the average energy expense of UEs on receiving data, and lower down the transmission power of BS. It thus helps achieve green communication for LTE-A networks.

We finally give some future work. First of all, LTE-A defines a *QoS class identifier (QCI)* for each flow to describe its QoS requirement [23]. It could be an interesting issue to schedule downlink resource for UEs when both CA and QCI have to be considered. In addition, how to efficiently manage resource in an LTE-A *heterogeneous network (HetNet)* [24] with CA deserves further investigation. In such HetNet environment, large macro-cells and small pico-cells will coexist to provide service, and it would be a challenge to deal with signal interference [25].

ACKNOWLEDGEMENTS

You-Chiun Wang's research is co-sponsored by the Ministry of Science and Technology under Grant No. MOST 104-2221-E-110-036-MY2 and 104-2628-E-110-001-MY2, Taiwan.

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