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Energy-Efficient Downlink Resource Scheduling for LTE-A Networks with Carrier Aggregation*

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To tackle the dilemma of supporting broadband, high-speed wireless access or well utilizing narrow, non-contiguous spectral resource, *Long Term Evolution–Advanced* (*LTE-A*) employs carrier aggregation. It combines different component carriers to send data to users in high rates. Many LTE-A downlink resource scheduling methods seek to assign component carriers or resource blocks to improve throughput or maintain fairness. However, how to save energy spent on communication has not been well studied. Thus, the paper formulates a *minimum-energy LTE-A downlink resource scheduling* (*MARS*) problem by using carrier aggregation to allocate resource to users, such that network throughput is improved while energy consumption is reduced. We show that the MARS problem is NP-hard and propose an efficient heuristic by considering data backlog, channel condition, and energy expense of users. Experimental results verify that our heuristic can increase system performance, conserve energy of user equipment, and reduce transmission power emitted from the base station.

Keywords: 4G system, carrier aggregation, energy saving, LTE-A, resource scheduling

1. INTRODUCTION

Due to the popularization of mobile devices, there has been a growing demand for wireless broadband service like video streaming and teleconference. Thus, ITU (International Telecommunication Union) regulates IMT-A (International Mobile Telecommunications-Advanced) for 4G systems, which provides 1Gbps and 500Mbps peak rates for downlink and uplink transmission, respectively. To meet IMT-A requirement, 3GPP (3rd Generation Partnership Project) defines *Long Term Evolution–Advanced* (*LTE-A*), which specifies the support for up to 100MHz channel bandwidth [1].

However, many frequency bands in the microwave spectrum have been dedicated to 2G/3G systems. It is not easy to find large, contiguous bands to meet IMT-A. To overcome the difficulty, LTE-A uses *carrier aggregation* to integrate multiple frequency segments (called *component carriers*, *CCs*). For example, LTE-A allows a base station (called *eNB*) to combine five 20MHz CCs to obtain 100MHz bandwidth. This technique is backward compatible with old LTE *user equipments* (*UEs*). Besides, the eNB can aggregate CCs located in different bands to improve the spectrum's utilization.

Carrier aggregation improves LTE-A performance, but how to efficiently schedule downlink resource is a challenge. Most LTE-A resource scheduling methods can be classified into two categories [2]: *CC selection* and *resource block* (*RB*) *assignment*. CC selection methods allocate downlink CCs to UEs to send data, while RB assignment meth-

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ods deal out RBs (*i.e.*, the substantiation of time-frequency resource in CCs) to UEs in a *transmission time interval* (*TTI*). Many methods seek to improve throughput by increasing channel quality of UEs or balancing loads among CCs. However, how to save energy spent on communication is rarely discussed. Due to carrier aggregation, UEs will consume more energy on hearing multiple CCs. Besides, to improve channel quality, the eNB has to emit higher transmission power on CCs, causing a waste of energy.

By the above motivation, we propose a *minimum-energy LTE-A downlink resource scheduling* (*MARS*) problem. Given traffic demands of UEs and the eNB's maximum power P_{max}, it asks how to assign downlink RBs to UEs such that 1) network throughput is maximized, 2) energy consumption of UEs is minimized, and 3) the eNB's transmission power is reduced. We show that MARS is NP-hard and develop an efficient heuristic. The idea is to let the eNB find the best *modulation and coding scheme* (*MCS*) for each (CC, UE) pair under P_{max} constraint. It then iteratively selects a CC to meet the demand of each UE and allocates RBs accordingly. However, unlike most methods where the 'best' CC is always given to the selected UE, the eNB should consider whether other UEs also prefer this CC. We thus define an *eagerness degree* to help the eNB select the proper CC, so as to help conserve UEs' energy. Finally, our heuristic adaptively adjusts the power on CCs to save the eNB's energy and reduce the interference to other cells.

Our contributions are threefold. First, we propose a MARS problem that considers throughput and energy consumption in LTE-A. Second, we prove that the MARS problem is NP-hard and develop an energy-efficient heuristic. Third, our heuristic maneuvers resource allocation based on traffic loads and noise levels of UEs. Simulation results show that our heuristic improves network throughput and saves energy of UEs and the eNB, as compared with both max-CQI and *proportional fair* (*PF*) methods.

This paper is organized as follows. Section 2 surveys LTE-A and related work. Section 3 defines the MARS problem. Sections 4 and 5 propose and discuss our heuristic. Experimental results are given in Section 6. A conclusion is drawn in Section 7.

2. PRELIMINARY

2.1 Downlink Spectral Resource in LTE-A

LTE-A proposes the 'frame-based' downlink transmission by using OFDMA (orthogonal frequency division multiple access). The length of a downlink frame is 10ms, which is divided into 10 subframes (also known as TTIs). Each subframe is composed of 2 slots. Thus, a slot has the length of 0.5ms, which contains 6 or 7 OFDM symbols. In LTE-A, RB is the unit for resource allocation, which occupies 1 slot and 12 consecutive subcarriers (in the same CC), where a subcarrier has 15kHz bandwidth. With different MCSs, each RB carries different number of data bits, as presented in Table 1. This determines the transmission speed for a UE using that RB.

To select MCS, the eNB emits a *downlink reference signal* for UEs to measure channel condition. A UE computes the *channel quality indicator* (*CQI*) such that it corresponds to the best MCS. Based on LTE-A specification [3], this MCS should allow the UE to decode data with *block error rate* (*BLER*) $\leq$ 10%. The UE then feeds back its CQI, which indicates the channel quality and receiver capability. Through CQI, the eNB can choose MCS and its code rate along with efficiency for that UE. These factors together determine the number of data bits carried by one RB for the UE (shown in Table 1).

Table 1. MCSs and data bits carried by an RB under different CQI values [3].

CQI	MCS	bits per RB	CQI	MCS	bits per RB
1	QPSK	12.79	10	64QAM	229.36
2	QPSK	19.69	11	64QAM	279.07
3	QPSK	31.67	12	64QAM	327.79
4	QPSK	50.53	13	64QAM	379.97
5	QPSK	73.67	14	64QAM	429.68
6	QPSK	98.77	15	64QAM	466.59
7	16QAM	124.03	QPSK: Quadrature phase shift keying QAM: Quadrature amplitude modulation		
8	16QAM	160.78			
9	16QAM	202.13			

To support backward-compatibility for LTE Release 8/9 UEs, LTE-A employs the same range of CC bandwidths. Each CC can have the bandwidth of 1.4, 3, 5, 10, 15, and 20MHz, which support 12, 30, 50, 100, 150, and 200 RBs in a TTI, respectively. LTE-A Release 10 [4] proposes both *intra-band* and *inter-band* carrier aggregation, where the eNB combines different CCs from the *same* and *different* frequency bands, respectively. Aggregating multiple CCs for data transmission improves efficiency. However, it also consumes more energy of a UE, because multiple *radio frequency* (*RF*) chains and *fast Fourier transform* (*FFT*) modules are required to hear different, non-contiguous CCs [5]. This motivates us to propose the MARS problem which considers not only carefully assigning CCs to each UE (to save its energy), but also reducing the transmission power on each CC (to save the eNB's energy and reduce interference).

2.2 Survey of CC Selection Methods

Based on [2], there are three common categories of 'static' CC assignment. *Random selection methods* [6, 7] arbitrarily choose available CCs for UEs to provide a balanced load among CCs in the long term. *Circular selection methods* [8, 9] assign CCs to UEs in a round-robin manner, which supports higher throughput than random selection methods. *Least load methods* [9, 10] always select the CC with the lowest traffic load to transmit data, so as to balance CCs' loads. However, they do not consider channel quality of CCs and traffic demands of UEs, which may degrade system performance.

Some studies consider 'dynamically' assigning CCs based on channel condition of UEs. Liu *et al.* [11] adaptively add/remove the secondary CC of a UE by its signal quality. Wang *et al.* [12] use a geometry factor to find cell-edge UEs, and assign low-frequency CCs (with better coverage) to improve their throughput. In [13], the CCs with similar channel quality are grouped together to improve spectrum utilization. A utility-based CC selection method is then proposed by taking channel quality and load balance into account. Li *et al.* [14] deal with CC selection by a micro-economic model, where the data rate of each CC is treated as a sale item, and UE's experience is viewed as a profit. Then, CCs are graded by the states of utilization with the goal of maximizing the total profit. However, these studies do not address the energy issue in LTE-A.

2.3 Survey of RB Assignment Methods

Several studies develop RB assignment strategies for LTE *without* carrier aggregation. In [15], RB assignment is formulated by an optimization problem whose goal is to keep UEs' fairness. Both [16] and [17] then use greedy-based and meta-heuristic methods to get suboptimal solutions to the problem, respectively. Wang *et al.* [18] assign RBs to different flows based on their channel quality, packet delay, and buffer length, which supports QoS (quality of service) for real-time service. Obviously, our MARS heuristic considers carrier aggregation, which distinguishes this paper from the above studies.

RB assignment with carrier aggregation has also been discussed. Motivating from PF scheduling [19], both [7, 20] seek to distribute downlink RBs to improve throughput and keep fairness. They give a higher priority to the UEs that currently have fast data rates or encounter slow data rates in the past. However, [7, 20] do not dynamically change the CCs assigned to each UE based on its channel quality. Cheng *et al.* [21] propose a backlog-based scheduling method to assign downlink resource to UEs, where backlog indicates the amount of unsatisfied demand of a UE. UEs with longer queue lengths or larger packet delays are given with a higher priority to select CCs, in order to achieve load balance and better throughput. Liao *et al.* [22] formulate an RB assignment problem with the MCS constraint, where a UE can use only one MCS for all its assigned RBs in each TTI. Then, a PF-based method is developed to improve network throughput while keeping fairness among UEs. Apparently, none of these work addresses energy consumption in LTE-A. On the contrary, our work targets at how to select CCs and adjust their transmission power, so as to conserve the energy spent on communication.

3. PROBLEM DEFINITION

We consider an LTE-A cell coordinated by one eNB, whose maximum transmission power is P_{max}. A set of UEs $\boldsymbol{U} = \{u_1, u_2, \ldots, u_m\}$ reside in the cell and ask for spectral resource, where $u_i \in \boldsymbol{U}$ has downlink data demand of d_i. Suppose that LTE-A spectrum is divided into a set of CCs $\boldsymbol{C} = \{c_1, c_2, \ldots, c_n\}$. The eNB can adjust its transmission power p_j on each CC $c_j \in \boldsymbol{C}$. Then, it should always satisfy the power constraint below:

$$\sum\nolimits_{c_j \in C} p_j \leq P_{\max}. \tag{1}$$

Depending on the channel bandwidth, each CC $c_j \in \boldsymbol{C}$ supports r_j RBs in a TTI. The carrier aggregation technique allows a UE to use the RBs located in different CCs. However, each UE is able to use up to δ CCs in one TTI (*e.g.*, $\delta = 5$ in LTE-A Release 10).

Let $b(j, k, l(i, j))$ be the number of data bits carried by an RB β_k in CC c_j under MCS $l(i, j)$ for a UE u_i. We define an indicator $I(i, j, k)$ to check whether RB β_k in CC c_j is allocated to UE u_i. Specifically, $I(i, j, k) = 1$ if so; $I(i, j, k) = 0$ otherwise. Then, our MARS problem asks how to select CCs and allocate their RBs to UEs, determines the MCS levels used by CCs, and adjusts the transmission power on each CC such that

$$\max \sum\nolimits_{u_i \in U} \min \left\{ \sum\nolimits_{j,k} [b(j,k,l(i,j)) \times I(i,j,k)],\ d_i \times t \right\}, \tag{2}$$

$$\min \sum\nolimits_{u_i \in U} P_{u_i}, \tag{3}$$

$$\min \sum\nolimits_{c_j \in C} p_j. \tag{4}$$

under constraint (1), where t is the length of a TTI, and P_{u_i} is the total power of UE u_i to receive data from its assigned CCs. Here, Eq. (2) wants to maximize the number of data bits transmitted. However, the eNB may allocate more resource than UE u_i needs (*i.e.*, $\Sigma_{j,k}[b(j, k, l(i,j)) \times I(i, j, k)] > d_i \times t$). In this case, we count the amount of data received by u_i (*i.e.*, $d_i \times t$). Then, Eq. (3) seeks to reduce the amount of energy consumed by all UEs. To find P_{u_i}, we employ the power model in [23]. It considers two types of UE receivers: 1) single RF front-end with single wide-band *analog-to-digital converter* (*ADC*) and dual *base band* (*BB*) processor, and 2) dual RF with dual narrow ADCs and dual BBs. Type-1 receiver is used only in intra-band contiguous carrier aggregation, where

$$P_{u_i} = P_{\text{RC}} + P_{\text{RF}}(S_{\text{RC}}) + P_{\text{ADC}}(\text{B}_{\text{RC}}) + \sum_{k=1}^{2}\left[P_{\text{BB}_k}(R_{\text{RC}_k}) + P_{\text{CW}} \times q_{\text{CW,cc}_k}\right]. \quad (5)$$

Here, P_{RC} is the base power consumed by the *receive chain* (*RC*), $P_{\text{RF}}(S_{\text{RC}})$ is the RF's power consumption (depending on power level S_{RC}), $P_{\text{ADC}}(B_{\text{RC}})$ is the ADC's power consumption (depending on bandwidth B_{RC}), $P_{\text{BB}}(R_{\text{RC}})$ is the BB's power consumption (depending on data rate R_{RC}), P_{CW} is the power consumption of using two code-words, and q_{CW} is the probability of using two code-words. On the other hand, type-2 receiver can be used in intra-band and inter-band non-contiguous carrier aggregation, where

$$P_{u_i} = 2P_{\text{RC}} + \sum_{k=1}^{2}\left[P_{\text{RF}_k}(S_{\text{RC}_k}) + P_{\text{ADC}_k}(B_{\text{RC}_k}) + P_{\text{BB}_k}(R_{\text{RC}_k}) + P_{\text{CW}} \times q_{\text{CW,cc}_k}\right]. \quad (6)$$

Finally, Eq. (4) means to minimize the eNB's transmission power. Theorem 1 proves the NP-hardness of the MARS problem. We also summarize our notations in Table 2.

Table 2. Summary of notations.

notation	definition
d_i	traffic demand of UE u_i
q_i	current backlog of UE u_i
p_j	transmission power allocated to CC c_j
r_j	number of available RBs in CC c_j
$e(i,j)$	eagerness degree of CC c_j for UE u_i
δ	maximum number of CCs that can be aggregated for a UE
P_{max}	maximum transmission power of the eNB
T_m	data-rate mapping table
$N(u_i, c_j)$	number of data bits supported by CC c_j for UE u_i
$b(j, k, l(i, j))$	number of data bits carried by an RB β_k in CC c_j under MCS $l(i, j)$

Theorem 1: The MARS problem is NP-hard.

Proof: Following the similar concept in [24], we first define a metric value

$$\alpha(i, j, k, l(i, j)) = \frac{\min\{b(j, k, l(i, j)), d_i \times t\}}{d_i \times t}, \quad (7)$$

for each UE u_i on an RB β_k in CC c_j under MCS $l(i, j)$; in other words, the metric value indicates the ratio of u_i's traffic demand satisfied by this RB in the current TTI. Then, we can define one decision version of our MARS problem by $\alpha(i, j, k, l(i, j))$. In particular, it determines whether for a given collection of values $\alpha(i, j, k, l(i, j))$ across all UEs, CCs, RBs, and MCSs, there can exist a resource scheduling solution to meet the constraint that each UE selects only one MCS and result in an aggregate value of D.

To prove the NP-hard property of MARS, we employ a well-known NP-complete problem, namely *three-satisfiability* (*3-SAT*) problem [25]. Given a set of clauses $\{L_1, L_2, \ldots, L_K\}$ based on a set of Boolean variables $X = \{x_1, x_2, \ldots, x_m\}$, where each clause contains three variables, 3-SAT asks whether there is a satisfying truth assignment. Here, a *clause* is a disjunction of three distinct terms (in the format of $T_1 \vee T_2 \vee T_3$, where each term T_i belongs to $\{x_1, x_2, \ldots, x_m, \neg x_1, \neg x_2, \ldots, \neg x_m\}$, and the notations '$\vee$' and '$\neg$' represent the 'OR' and 'NOT' operators, respectively). A *truth assignment* for X is an assignment of the value 0 or 1 to every variable x_i. We say that an assignment 'satisfies' a set of clauses $L_1, L_2, \ldots, L_K$ if and only if it makes the result of each clause L_i to be 1 according to the rules of Boolean logic. In other words, the result of conjunction $L_1 \wedge L_2 \wedge \ldots \wedge L_K$ must be also 1, where the notation '$\wedge$' represents the 'AND' operator.

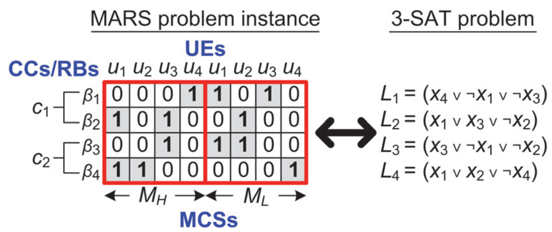


Fig. 1. An example of reducing the 3-SAT problem to one MARS problem instance.

We then reduce the 3-SAT problem to a MARS problem instance. Specifically, we are given any instance of 3-SAT that has m variables (*i.e.*, $x_1, x_2, \ldots, x_m$) and K clauses (*i.e.*, $L_1, L_2, \ldots, L_K$). Let us consider an LTE-A network with two MCS levels (denoted by M_H and M_L). Then, each UE in $\boldsymbol{U}$ corresponds to a variable in 3-SAT. In particular, for each variable x_i and its negation $\neg x_i$, we have a UE u_i that uses MCS M_H and M_L to receive data, respectively. Moreover, each RB corresponds to one clause in 3-SAT, so we have m UEs and K RBs in the MARS instance. Fig. 1 gives an example with four variables and four clauses, where gray RBs correspond to the 3-SAT terms appearing in their clauses. Since each RB can be allocated to at most one UE, it allows us to choose one single term in each clause of 3-SAT whose result will be 1. Then, we transform the values $\alpha(i, j, k, l(i, j))$ in the MARS instance into the conflicts in 3-SAT, where two terms are called *conflict* if one is equal to a variable x_i while the other is equal to its negation $\neg x_i$. In the MARS instance, either M_H or M_L can be assigned to each UE. It thus proves that the MCS constraint well fits the conflicting operation in 3-SAT. Specifically, for each RB β_k, we set $\alpha(i, j, k, M_H) = 1$ when x_i appears in clause L_k, and $\alpha(i, j, k, M_L) = 1$ when $\neg x_i$ is in L_k. If L_k contains neither x_i nor $\neg x_i$, we define $\alpha(i, j, k, l(i, j)) = 0$. Then, we set the aggregate value D to K (*i.e.*, the number of clauses in 3-SAT), so as to finish constructing the MARS instance.

We argue that our reduction is correct by showing that the MARS problem instance has a feasible solution if and only if the 3-SAT problem has a feasible solution:

[If part] Suppose that there is a solution $S_{3\text{-SAT}}$ to the 3-SAT problem. Then, for each variable $x_i \in S_{3\text{-SAT}}$, we can allocate a corresponding RB with MCS M_H to UE u_i. Similarly, we can allocate a corresponding RB with MCS M_L to UE u_i when a negation $\neg x_i$ belongs to $S_{3\text{-SAT}}$. In this way, each RB in the MARS instance can be assigned to one UE with MCS $l(i, j)$ whose metric value $\alpha(i, j, k, l(i, j)) = 1$. Notice that it is impossible to set MCS $l(i, j)$ to M_H and M_L simultaneously, as the corresponding terms in 3-SAT will conflict with each other.

[Only if part] Suppose that there is a solution S_{MARS} to the MARS instance, where it must assign one UE with $\alpha(i, j, k, l(i, j)) = 1$ for every RB. We then show that there will exist a satisfying truth assignment A in 3-SAT. Specifically, for each variable x_i, if a UE u_i is not assigned in S_{MARS}, we arbitrarily set $A(x_i) = 1$. Otherwise, S_{MARS} must select exactly one MCS for u_i. When S_{MARS} chooses M_H, we can set $A(x_i) = 1$; on the other hand, we set $A(x_i) = 0$ if S_{MARS} chooses M_L. In this way, all clauses in 3-SAT can be evaluated to 1 by the truth assignment A (*i.e.*, we find a feasible solution to 3-SAT).

Based on the above argument, we prove that the MARS problem is NP-hard. ❑

4. THE PROPOSED MARS HEURISTIC

Given the power constraint P_{max} and traffic demands of all UEs, our MARS heuristic involves the following steps:

[Step 1] The eNB equally distributes its power to all CCs, so each CC $c_j \in \boldsymbol{C}$ is allocated with an amount ($p_j = P_{max}/|\boldsymbol{C}|$) of power. Following LTE-A specification (referring to Section 2.1), the eNB sends a reference signal to all UEs based on this power. A UE then evaluates its channel quality on CCs. It is done by measuring SINR (signal-to-interference-plus-noise ratio) on every CC and finding the highest CQI, such that BLER ≤ 10%. Then, the UE feeds back its CQI measurement to the eNB for reference.

[Step 2] With CQI, the eNB finds the best MCS for each (UE, CC) pair. From Table 1, the eNB builds a *data-rate mapping table* T_m, where each tuple (u_i, c_j) records the number of data bits $N(u_i, c_j)$ that can be transmitted by a CC $c_j \in \boldsymbol{C}$ for a UE $u_i \in \boldsymbol{U}$:

$$N(u_i, c_j) = b(j, k, l(i, j)) \times r_j, \tag{8}$$

where u_i uses MCS $l(i, j)$ and c_j has r_j RBs. For example, suppose that c_j has 5MHz bandwidth and u_i reports CQI = 7. Then, we have $b(j, k, l(i, j)) = 124.03$ and $r_j = 50$. Thus, the number of data bits transmitted by c_j for u_i is $N(u_i, c_j) = 124.03 \times 50 \approx 6201$.

[Step 3] For each UE $u_i \in \boldsymbol{U}$, we use a variable q_i to indicate how many data bits have not been sent yet (called *backlog*), which is initially set to $d_i \times t$. Then, the UE with the largest q_i value, say, u_i is selected for resource allocation. The eNB will assign one CC (and allocate its RBs) to u_i by the three rules:

- **Rule 1:** If only one CC c_j can satisfy UE u_i's backlog (*i.e.*, $N(u_i, c_j) \geq q_i$), the eNB assigns c_j to u_i, and allocates a number of $x_i = \lceil q_i / b(j, k, l(i, j)) \rceil$ RBs to send u_i's data. Then, we deduct x_i from r_j. For each $u_k \in \boldsymbol{U}$, its $N(u_k, c_j)$ value in table Tm is recomputed by Eq. (8). Besides, we set $q_i = 0$ since u_i's entire backlog has been satisfied.

- **Rule 2:** If a subset $\boldsymbol{Cs} \subseteq \boldsymbol{C}$ of CCs each can satisfy UE u_i's backlog, where $|\boldsymbol{Cs}| \geq 2$, the eNB compares their *eagerness degrees*. Specifically, for each CC $c_j \in \boldsymbol{Cs}$, its eagerness degree (for UE u_i) is defined by

$$e(i, j) = \sum\nolimits_{\forall u_k \in U} \{N(u_k, c_j) \mid u_k \neq u_i \text{ and } q_k > 0\}, \tag{9}$$

  which is the sum of data bits supported by c_j for all other UEs with positive backlog (except u_i). Here, a smaller $e(i, j)$ value implies that most of other UEs have worse channel quality on c_j. In this case, it can cause less effect on other UEs when u_i selects c_j to receive data, because the average data rate for other UEs on c_j is small (and thus they do not prefer using c_j). Thus, the eNB can assign CC c_a in $\boldsymbol{Cs}$ with the minimum eagerness degree for UE u_i. Following Rule 1, we will also update variables r_a, $N(u_k, c_a)$, and q_i accordingly.
- **Rule 3:** If no single CC can satisfy UE u_i's backlog (*i.e.*, $N(u_i, c_a) < q_i$ for all $c_a \in \boldsymbol{C}$), the eNB picks the CC, say, c_j with the maximum $N(u_i, c_j)$ value. In case of tie, it chooses the CC c_j with the minimum eagerness degree $e(i, j)$. The eNB sets $N(u_k, c_j) = 0$ in table T_m for each $u_k \in \boldsymbol{U}$, because it has allocated all RBs in c_j to u_i, and thus c_j cannot support any UE. Then, u_i's backlog is updated by $q_i - N(u_i, c_j)$.

Here, a UE consumes more energy to receive data from non-contiguous CCs. Thus, we can adaptively adjust the eagerness degrees of some CCs to increase the possibility that a UE will use contiguous CCs for communication. Suppose that a CC c_j has been assigned to a UE u_i. If another CC, say, c_k and c_j are contiguous, we multiply its eagerness degree by a *scaling factor* σ (*i.e.*, $e(i, j) = \sigma \times e(i, j)$), where $0 < \sigma < 1$. Thus, there will be a high possibility that the eNB also assigns c_k to u_i by using Rule 2 or 3. Since c_j and c_k are contiguous, u_i can significantly save its energy when applying carrier aggregation.

[Step 4] The eNB iteratively executes step 3 to select CCs and allocate RBs to UEs, until any of the three cases occurs:
1. The backlog of each UE becomes zero.
2. Table T_m has no non-zero $N(u_i, c_j)$ value, but there is one UE with positive backlog.
3. A UE u_i has been assigned with δ CCs, but it still has residual backlog.

Case 1 indicates that the demands of all UEs are satisfied (*i.e.*, the overall throughput is maximized). Thus, we can execute step 5 to further reduce the eNB's transmission power. Case 2 occurs when the eNB has no sufficient resource for all UEs. In this case, it is difficult to lower the power on any CC, so the eNB skips step 5 and allocates all RBs to UEs based on the scheduling result. Case 3 means that the eNB can no longer allocate RBs to UE u_i (or it will violate LTE-A specification). Thus, the eNB removes u_i from $\boldsymbol{U}$ (but still gives u_i its allocated RBs) and goes back to step 3 to schedule other UEs.

[Step 5] For each assigned CC, the eNB checks if it can save the transmission power while still satisfying the demands of UEs. Let us consider a simple case where a CC c_j is assigned to only one UE u_i. Suppose that the power calculated in step 1 allows the eNB to use an MCS level $l(i, j)$ for c_j. Then, the eNB iteratively tries to use the MCS level lower than $l(i, j)$, and checks if the RBs assigned to u_i can support its demand. If so, the eNB recalculates the new power p_j for CC c_j based on its SINR value and the new MCS level. We then discuss the complex case where a CC c_j is assigned to a set of UEs $\boldsymbol{Us} \subseteq$

U. Let p_j be the current power on CC c_j and $p_j(i)$ denote the new power calculated from UE u_i's perspective (using the above method). Obviously, we have $p_j(i) \le p_j$ for all $u_i \in$ ***Us***. Then, the new transmission power on CC c_j will be

$$p_j = \max_{u_i \in U_S} p_j(i). \tag{10}$$

Here, since CC c_j is shared by multiple UEs, we have to take care of each such UE when reducing the transmission power. That is why we take the maximum value in Eq. (10).

Table 3. An example of the data-rate mapping table T_m.

UE	c_1	c_2	c_3	c_4	c_5	c_6
u_1	606 (4)	606 (4)	380 (3)	606 (4)	606 (4)	236 (2)
u_2	153 (1)	606 (4)	380 (3)	380 (3)	884 (5)	380 (3)
u_3	153 (1)	236 (2)	236 (2)	153 (1)	380 (3)	884 (5)

We give an example to demonstrate our heuristic, where $\boldsymbol{U} = \{u_1, u_2, u_3\}$ and $\boldsymbol{C} = \{c_1, c_2, \ldots, c_6\}$ (in the same band). Each CC has 1.4MHz bandwidth and supports 12 RBs. We set $\sigma = 0.5$ and T_m is given in Table 3, where each number in brackets indicates the CQI index. UEs u_1, u_2, and u_3 have data demands of 1200, 1150, and 600 bits in a TTI, respectively. Then, the MARS heuristic will execute the following iterations:

1. The eNB first picks UE u_1 (with the largest backlog) and uses Rule 3. CCs c_1, c_2, c_4, and c_5 will be candidates, and their eagerness degrees are $e(1, 1) = 153 + 153 = 306$, $e(1, 2) = 606 + 236 = 842$, $e(1, 4) = 380 + 153 = 533$, and $e(1, 5) = 884 + 380 = 1264$, respectively. In this case, we prefer selecting c_1, because comparing with c_1, all other candidates (c_2, c_4, and c_5) can allow other UEs (u_2 and u_3) to enjoy higher data rates. In other words, selecting c_1 for u_1 can have the least impact on other two UEs. Then, we set $N(u_1, c_1) = N(u_2, c_1) = N(u_3, c_1) = 0$, and update $q_1 = 1200 - 606 = 594$.
2. UE u_2 is chosen and Rule 3 is used, so CC c_5 is the only candidate. The eNB assigns c_5 to u_2, sets $N(u_1, c_5) = N(u_2, c_5) = N(u_3, c_5) = 0$, and updates $q_2 = 1150 - 884 = 266$.
3. The eNB chooses UE u_3. Since only CC c_6 can satisfy u_3's backlog, Rule 1 is adopted. However, u_3 requires just $\lceil 600/73.67 \rceil = 9$ RBs, so c_5 remains $12 - 9 = 3$ RBs. Thus, the eNB assigns c_5 to u_3, sets $N(u_1, c_5) = 19.69 \times 3 \approx 59$, $N(u_2, c_5) = 31.67 \times 3 \approx 95$, $N(u_3, c_5) = 73.67 \times 3 \approx 221$, and updates $q_3 = 0$.
4. The eNB picks UE u_1 again. Here, since CCs c_2 and c_4 can satisfy u_1's residual backlog, Rule 2 is applied. Thus, the eNB computes their eagerness degrees as follows:

$$e(1,2) = \sum \{N(u_k, c_2) \mid u_k \ne u_1, q_k > 0\} \times \sigma = N(u_2, c_2) \times 0.5 = 303,$$
$$e(1,4) = \sum \{N(u_k, c_4) \mid u_k \ne u_1, q_k > 0\} = N(u_2, c_4) = 380.$$

   Since u_1 has been assigned with CC c_1 in iteration 1 and CCs c_1 and c_2 are contiguous, u_1 prefers c_2 than c_4. This is realized by multiplying c_2's eagerness degree $e(1, 2)$ by σ. Then, the eNB sets $N(u_1, c_2) = N(u_2, c_2) = N(u_3, c_2) = 0$, and updates $q_1 = 0$.
5. Then, only UE u_2 has residual backlog. By Rule 2, CCs c_3 and c_4 become candidates, but their eagerness degrees are both zero (based on Eq. (8)). In this case, the eNB assigns c_4 to u_2, since CC c_5 has been assigned to u_2, and both c_4 and c_5 are contiguous.

Thus, UEs u_1, u_2, and u_3 are assigned with CCs $\{c_1, c_2\}$, $\{c_4, c_5\}$, and $\{c_6\}$, respectively. The eNB can employ *contiguous* carrier aggregation to save UEs' energy. Finally, by step 5, the eNB checks if it can lower MCS to save the power on each CC. In particular, it can change the MCS of CC c_6 from CQI = 5 to CQI = 4. Thus, c_5 can support 50.53 × 12 ≈ 606 bits, which satisfies UE u_3's demand (*i.e.*, 600 bits). In this case, the eNB can reduce the power on c_6 to save its energy, and also reduce the interference to other cells.

5. DISCUSSION ON THE MARS HEURISTIC

We discuss the rationale of our heuristic, which involves four special designs. First, in the MARS problem, the eNB should not only determine the CC assignment for UEs, but also estimate the transmission power on each CC. These two factors could affect with each other, making the problem complex. Thus, step 1 fixes one factor by giving the 'default' power on CCs, so the eNB can use a data-rate mapping table for reference. Then, the eNB tries to reduce the power on each assigned CC in step 5 if the UE has a lower noise level. It has two advantages to use the default power. On one hand, the proposed heuristic is relatively simple for the eNB to execute in every short TTI period. On the other hand, the eNB actually considers the 'worst' case in the beginning (*i.e.*, all CCs consume the maximum power P_{max}). This can help the eNB determine whether the system resource is enough to satisfy the demands of all UEs.

Second, many existing methods directly assign the 'best' CC c_j to the selected UE u_i. However, other UEs could be 'eager' for c_j as they have better channel quality on c_j. Once c_j is given to u_i, other UEs would have to use CCs with worse channel condition. In this case, the eNB may need to aggregate more CCs to meet their demands, thereby not only wasting more resource but also forcing UEs to spend more energy. To solve this problem, our heuristic uses eagerness degrees in step 3. When the selected UE u_i has multiple choices of CCs, the eNB selects the CC c_k with the minimum eagerness degree for u_i, where other UEs do not have good channel quality on c_k. In this way, assigning c_k to u_i can have less impact on other UEs whose demands have not been satisfied yet.

Third, a UE can preserve more energy if it uses contiguous CCs to receive data by Eqs. (5) and (6). To address this issue, we scale down the eagerness degree of a contiguous CC by a factor σ. Because our MARS heuristic always asks the UE to select the CC with the minimum eagerness degree, the above design can increase the opportunity that the UE selects the contiguous CC to receive data. This design is also lightweight, so the eNB can avoid complicated calculation.

Fourth, we discuss two abnormal cases in step 4, where the eNB has no sufficient resource to meet the demands of some UEs. We have two solutions to deal with them. One solution is that the eNB invokes *call admission control* [26] to ask these UEs to decrease their demands or decline some UEs with excessive requests. Thus, the eNB can allocate RBs to satisfy the modified demands of all UEs. Alternatively, the eNB can keep the unsatisfied demands for *next-TTI scheduling*. Since our heuristic first selects the UE with the maximum demand, a UE with more unsatisfied demand in the previous TTI will have a higher opportunity to be allocated with RBs first in the next TTI.

We finally analyze the time complexity of our MARS heuristic in Theorem 2.

Theorem 2: Given m UEs and n CCs, the MARS heuristic spends $O(m\delta \times (n + m))$ time to schedule RBs for UEs in the worst case.

Proof: In our heuristic, step 1 takes $O(1)$ time since it is trivial to find the transmission power on each CC. In step 2, the eNB builds table T_m for reference, which takes $O(mn)$ time. For step 3, it spends $O(m)$ time to calculate the backlog of each UE. Then, the eNB can use a maximum binary heap to store all UEs by their backlog values, which requires $O(m)$ time. To speed up step 3, the eNB keeps a table to store the eagerness degree $e(i, j)$ for each pair of UE u_i and CC c_j. From Eq. (9), $e(i, j)$ is the sum of all $N(u_k, c_j)$ values for each $u_k \neq u_i$. Because there are n CCs, building this table requires $O(n(m - 1))$ time. Since a UE can be given with at most δ CCs, the eNB will repeat step 3 for at most $O(m\delta)$ times. Each iteration of step 3 involves the following operations:

- Get UE u_i with the maximum backlog from the heap, which requires $O(\lg m)$ time.
- Find a CC by the three rules. It takes $O(n)$ time since the eNB has to search all CCs.
- The eNB updates the eagerness degree $e(k, j)$ for each pair of UE u_k and CC c_j, where $u_k \neq u_i$. This operation spends $O(m - 1)$ time.
- If UE u_i still has positive backlog, the eNB inserts u_i into the heap for scheduling later. This operation takes $O(\lg m) + O(1) = O(\lg m)$ time.

Steps 3 and 4 together thus spend time of $O(m) + O(m) + O(n(m - 1)) + O(m\delta) \times [O(\lg m) + O(n) + O(m - 1) + O(\lg m)] = O(m\delta \times (n + m - 1))$. Finally, each UE is assigned with at most δ CCs, so step 5 needs to check at most $O(m\delta)$ pairs of UEs and CCs to save the power on each CC. Thus, our MARS heuristic totally requires $O(1) + O(mn) + O(m\delta \times (n + m - 1)) + O(m\delta) = O(m\delta \times (n + m))$ time. ❑

6. PERFORMANCE EVALUATION

We develop a simulator in C++ to evaluate the performance of our MARS heuristic. Following LTE-A Release 10 [4], two frequency bands are adopted: Band 1 (2110MHz~2170MHz) and Band 5 (869MHz~894MHz). Band 1 is cut into twelve 5MHz CCs, while Band 5 is cut into two 5MHz CCs and five 3MHz CCs. Thus, we have $|\boldsymbol{C}| = 19$. We consider an LTE-A macro-cell where a number of UEs randomly reside. There are six eNBs deployed outside the macro-cell to generate noise on different CCs. The *log-distance path loss model* is used to simulate radio propagation of wireless communication:

$$PL = 128.1 + 37.6\log_{10}\text{dist}(\text{eNb}, u_i). \tag{11}$$

where PL is the path loss (in milliwatts) and dist(eNB, u_i) denotes the distance between the eNB and UE u_i (in kilometers). The eNB can aggregate up to 5 CCs for a UE to receive its data (*i.e.*, $\delta = 5$). Besides, each UE generates its traffics according to Table 4.

Table 4. Traffic demands of UEs in simulations.

traffic type	average bit rate	ratio
VoIP (G.711 standard)	64 Kbps	4/15
IPTV (H.264 standard)	128 Kbps	4/15
HTTP/FTP	169 Kbps	4/15
video (low quality)	21.8 Mbps	1/15
video (medium quality)	28.3 Mbps	1/15
video (high quality)	34.4 Mbps	1/15

We compare our heuristic with two resource scheduling methods. The *PF* method in [22] computes the 'weighted' transmission rate of a UE on each CC, and selects the maximum one. To keep PF among UEs, a larger weight is given to a UE that sent less data (and vice versa). The *max-CQI* method in [27] always selects the UE with the best channel quality to use each CC. In our MARS heuristic, we set $\sigma = 0.5$. For each experiment, we conduct 1000 simulations and take their average. Remark 1 discusses our measurement of overheads in communication and carrier aggregation in the simulations.

Remark 1: (Overheads in communication and carrier aggregation)

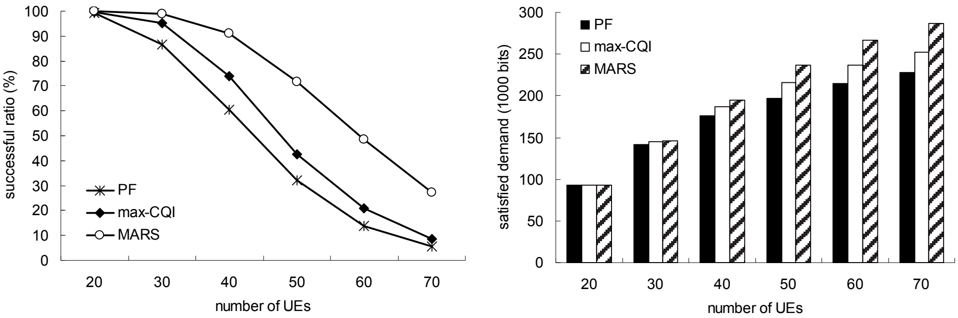
In MARS, the overhead in communication only occurs in step 1, as the eNB has to emit the downlink reference signal and all UEs need to report their CQI indices. Other steps only involve the calculation in the eNB, which requires no overhead in communication. However, step 1 is the necessary operation defined in the LTE-A standard [3]. In other words, both PF and max-CQI methods also require step 1 to obtain the information of channel condition of every CC, or otherwise their scheduling algorithms cannot work. Thus, we do not evaluate the overhead in communication, because it will be the same for each method (and also for the original proposal of LTE-A).

On the other hand, the overhead in carrier aggregation reflects on the energy consumption of UEs. As discussed in Section 3, a UE consumes more energy on receiving data from multiple CCs according to Eqs. (5) and (6). Therefore, we measure the average amount of energy spent by each UE on receiving downlink data to evaluate the overhead in carrier aggregation. Moreover, we will also measure the average number of CCs used by each UE. Obviously, when more CCs are used, the UE will incur a higher overhead in carrier aggregation, as it has to simultaneously listen to more CCs. ❑

6.1 Effect of Different Number of UEs

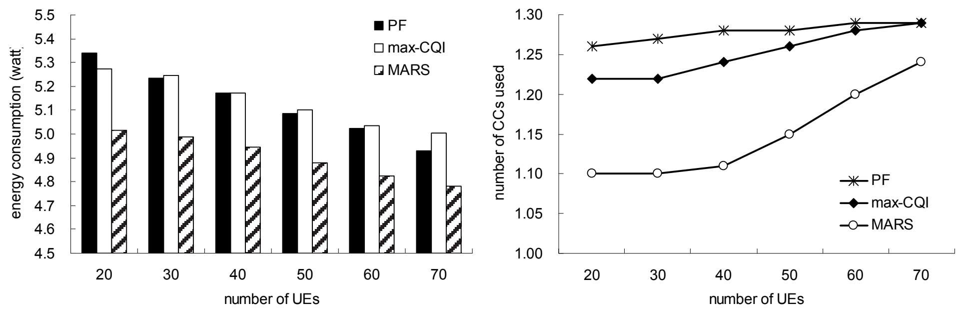
By changing the number of UEs, we study its effect on scheduling results, where P_{max} = 40watts. Fig. 2 (a) shows the *successful ratio* of resource scheduling, which is defined by the ratio of the number of simulations that the eNB satisfies the demands of all UEs to the total 1000 ones. When there are more UEs, the ratio decreases as more UEs compete for the fixed resource. Since the PF method has fairness concern, it may not give enough resource to the UEs with better channel quality, thereby decreasing the ratio. By considering the backlog, channel quality, and eagerness degree, MARS always has the highest ratio. Even though there are 70 UEs in the cell (*i.e.*, a dense scenario), it still can keep around 30% of the successful ratio (but other two methods have less than 10%). On the other hand, Fig. 2 (b) presents the *average satisfied demand* of each UE. We can observe that MARS outperforms other methods, especially when there are more UEs. This verifies the effectiveness of our heuristic in terms of resource allocation.

We then evaluate the amount of resource spent by each UE. Fig. 3 (a) gives the average energy consumption of UEs. Since the number of CCs and P_{max} are constant, the amount of resource does not change. When there are more UEs, each one is given less resource. Thus, a UE does not spend much energy to use its resource. That is why the energy consumption decreases when the number of UEs grows. Since the PF method allocates less resource to UEs than the max-CQI method does, it lets each UE consume less energy. However, the PF and max-CQI methods do not prefer assigning contiguous CCs to UEs, so they may force each UE to spend more energy to hear non-contiguous



(a) Successful ratio. (b) Satisfied demand.

Fig. 2. Comparison on the scheduling results under different number of UEs.



(a) Energy consumption. (b) Number of CCs used.

Fig. 3. Comparison on the amount of resource spent under different number of UEs.

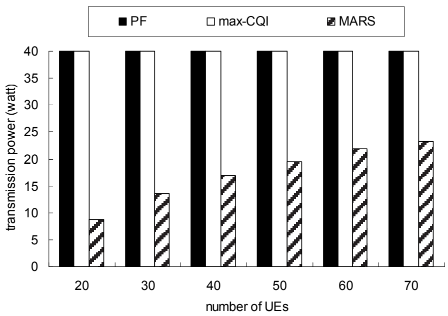


Fig. 4. Comparison on the eNB's transmission power under different number of UEs.

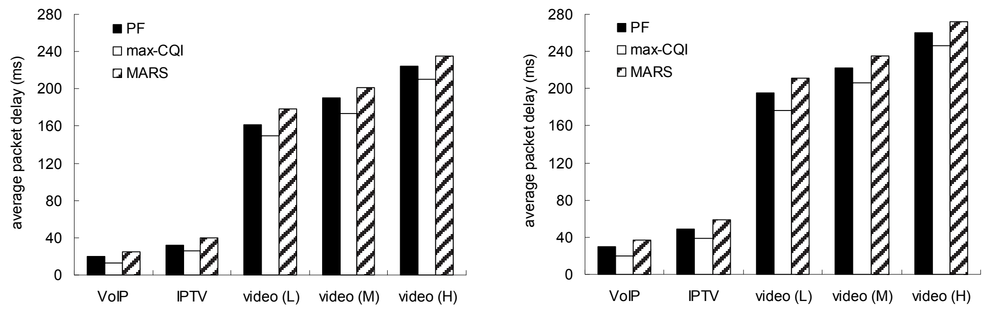
CCs. On the contrary, our MARS heuristic encourages UEs to receive data from contiguous CCs. Thus, UEs can significantly save their energy. Fig. 3 (b) gives the average number of CCs assigned to each UE. As the number of UEs increases, the eNB would need to aggregate more CCs to satisfy the growing demand. By using the eagerness degree, MARS can reduce the number of CCs used by a UE, thereby preserving its energy.

Fig. 4 shows the eNB's transmission power. Since both PF and max-CQI do not consider saving the eNB's energy, they always ask the eNB to emit the maximum power, which wastes resource. On the contrary, MARS decreases the transmission power on each assigned CC (in step 5) by using lower MCS levels if feasible. Thus, without decreasing system performance, it can reduce the eNB's transmission power while satisfying the traffic demands of UEs. Notice that when there are more UEs, the eNB should try to improve the channel quality of each CC in order to satisfy the growing demand, so the transmission power increases as the number of UEs increases in MARS. Table 5 summarizes the performance improvement by MARS under different number of UEs.

Table 5. Performance improvement by MARS under different number of UEs.

UEs	20	30	40	50	60	70	average
Successful ratio of scheduling							
PF	0.6%	14.1%	50.7%	123.1%	248.9%	398.2%	139.3%
max-CQI	0.4%	3.9%	23.0%	68.9%	133.2%	222.4%	75.3%
Average satisfied demand							
PF	0.1%	3.0%	10.8%	20.1%	24.7%	25.8%	14.1%
max-CQI	0.0%	0.5%	4.5%	10.1%	12.9%	13.9%	7.0%
Average energy consumption of UEs							
PF	6.1%	4.7%	4.3%	4.1%	3.9%	2.9%	4.3%
max-CQI	4.9%	4.9%	4.4%	4.4%	4.2%	4.4%	4.5%
Average number of CCs used							
PF	12.7%	13.4%	13.3%	10.2%	7.0%	3.9%	10.1%
max-CQI	9.8%	9.8%	10.5%	8.7%	6.3%	3.9%	8.2%
eNB's transmission power							
both	78.3%	66.1%	57.8%	51.4%	45.2%	41.8%	56.8%

We remark that MARS seeks to save the eNB's energy consumption by selecting lower MCSs for data transmission. This operation may affect packet latency of some flows. Thus, we conduct an experiment to evaluate the average packet delay of real-time flows, as shown in Fig. 5, where 'L', 'M', and 'H' respectively denote 'low quality', 'medium quality', and 'high quality' of videos. Apparently, when the number of UEs grows, the packet delay increases accordingly. The max-CQI method has the lowest packet delay, as it always chooses the UE with the best channel quality to use each CC. Nevertheless, such low delay is at the sacrifice of successful ratio of scheduling, energy



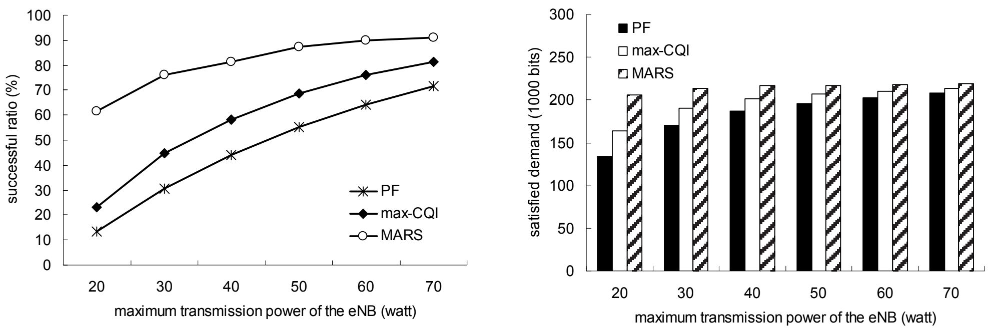
(a) 40UEs. (b) 60UEs.

Fig. 5. Comparison on average packet delay of different methods.

consumption of UEs, and eNB's transmission power (referring to Figs. 2-4). On the other hand, MARS adopts the eagerness degree to increase the successful ratio of scheduling, and lowers MCSs to reduce the eNB's transmission power when feasible. It thus incurs slightly higher packet delay than other two methods. However, since MARS significantly improves the amount of satisfied demand of UEs (referring to Fig. 2), it can also increase the opportunity of meeting the transmission demand of real-time flows.

6.2 Effect of Different P_{max} Power

By increasing P_{max} from 20 to 70watts, we measure its effect on different methods. In this experiment, there are 45 UEs, and Fig. 6 shows the simulation results. When P_{max} is enlarged, it means that the total spectral resource increases, as the eNB can transmit higher power to improve channel quality of CCs. Thus, not only the successful ratio of resource scheduling but also the satisfied demand of UEs increases when P_{max} grows. Our MARS heuristic always has the best performance among all methods, because it does not simply assign the best CC to the selected UE. Instead, MARS will consider the eagerness degree of each CC, so as to get better resource allocation.

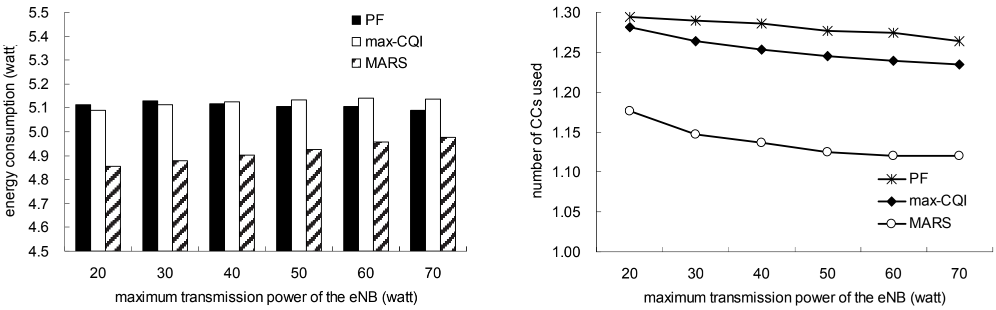


(a) Successful ratio. (b) Satisfied demand.

Fig. 6. Comparison on the scheduling results under different P_{max} power.

Fig. 7 presents the amount of resource spent by each UE under different P_{max} power. Because the total number of CCs is fixed, increasing P_{max} only slightly increases the energy consumption of each UE (since the UE still listens to similar number of CCs). In addition, when P_{max} grows, the probability that the eNB employs fewer CCs to satisfy the demand of each UE increases. Therefore, the number of CCs used by each UE can also slightly decreases. From Figs. 7 (a) and (b), our MARS heuristic can help UEs spend less resource (*i.e.*, energy and CCs) to meet its demand.

We then measure the eNB's transmission power under different P_{max} power, as shown in Fig. 8. Because both PF and max-CQI do not take the eNB's energy consumption into account, they will ask the eNB to use the maximum power to serve all UEs. By adaptively adjusting the transmission power on each CC, our MARS heuristic allows the eNB to use less energy to satisfy the demands of its UEs. Finally, we summarize the performance improvement by MARS under different P_{max} power in Table 6.



(a) Energy consumption. (b) Number of CCs used.

Fig. 7. Comparison on the amount of resource spent under different P_{max} power.

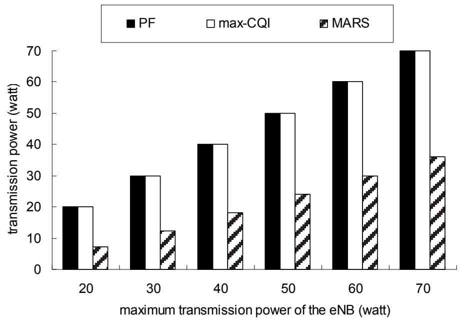


Fig. 8. Comparison on the eNB's transmission power under different P_{max} power.

Table 6. Performance improvement by MARS under different P_{max} power.

P_{max}	20	30	40	50	60	70	average
Successful ratio of scheduling							
PF	363.2%	149.8%	84.1%	58.2%	39.8%	27.1%	120.4%
max-CQI	165.5%	70.1%	39.5%	27.1%	18.0%	12.2%	55.4%
Average satisfied demand							
PF	54.3%	24.9%	16.0%	10.9%	7.4%	5.1%	19.8%
max-CQI	25.9%	12.1%	7.9%	5.1%	3.6%	2.5%	9.5%
Average energy consumption of UEs							
PF	5.0%	4.8%	4.2%	3.5%	2.9%	2.3%	3.8%
max-CQI	4.6%	4.6%	4.4%	4.0%	3.6%	3.2%	4.1%
Average number of CCs used							
PF	9.1%	11.1%	11.6%	11.9%	12.1%	11.4%	11.2%
max-CQI	8.2%	9.3%	9.3%	9.6%	9.6%	9.3%	9.2%
eNB's transmission power							
both	64.4%	58.7%	54.4%	51.9%	50.3%	48.3%	54.7%

7. CONCLUSION

Carrier aggregation greatly improves spectrum utilization of LTE-A, but the standard leaves the problem of allocating resource to implementers. Many solutions are thus proposed to increase network throughput or keep transmission fairness. However, most of them do not consider the energy spent in communication. To deal with the issue, this paper formulates an NP-hard MARS problem with the objectives of satisfying traffic demands of UEs while reducing energy consumption in the network. We develop a heuristic by adopting the novel eagerness degree to help the eNB select a proper CC for each UE, which increases the opportunity that other UEs can be also assigned with better CCs for transmission. Moreover, the proposed heuristic adaptively adjusts MCSs used in some CCs to further save the overall transmission power. Our MARS heuristic is lightweight and efficient. By comparing with both PF and max-CQI methods through simulations, we demonstrate that the MARS heuristic can increase 55.4%-139.3% of successful ratio of scheduling, 7.0%-19.8% of average satisfied demand, 3.8%-4.5% of average energy consumption of UEs, 8.2%-11.2% of average number of CCs used, and 54.7%-56.8% of the eNB's transmission power, under various experimental scenarios.

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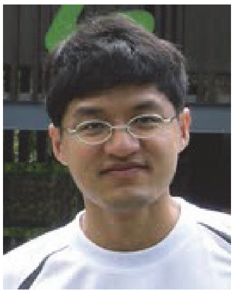
REFERENCES

1. A. Ghosh, R. Ratasuk, B. Mondal, N. Mangalvedhe, and T. Thomas, "LTE-advanced: next-generation wireless broadband technology," *IEEE Wireless Communications*, Vol. 17, 2010, pp. 10-22.
2. H. Lee, S. Vahid, and K. Moessner, "A survey of radio resource management for spectrum aggregation in LTE-advanced," *IEEE Communications Surveys and Tutorials*, Vol. 16, 2014, pp. 745-760.
3. 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures," TS 36.213, June 2012.
4. 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (Release 10)," TS 36.101, October 2014.
5. Z. Shen, A. Papasakellariou, J. Montojo, D. Gerstenberger, and F. Xu, "Overview of 3GPP LTE-advanced carrier aggregation for 4G wireless communications," *IEEE Communications Magazine*, Vol. 50, 2012, pp. 122-130.
6. H. Tian, S. Gao, J. Zhu, and L. Chen, "Improved component carrier selection method for non-continuous carrier aggregation in LTE-advanced systems," in *Proceedings of IEEE Vehicular Technology Conference*, 2011, pp. 1-5.
7. Y. Wang, K. I. Pedersen, T. B. Sorensen, and P. E. Mogensen, "Carrier load balancing and packet scheduling for multi-carrier systems," *IEEE Transactions on Wireless Communications*, Vol. 9, 2010, pp. 1780-1789.
8. L. Zhang, F. Liu, L. Huang, and W. Wang, "Traffic load balance methods in the LTE-advanced system with carrier aggregation," in *Proceedings of IEEE International Conference on Communications, Circuits and Systems*, 2010, pp. 63-67.
9. L. Zhang, K. Zheng, W. Wang, and L. Huang, "Performance analysis on carrier scheduling schemes in the long-term evolution-advanced system with carrier aggregation," *IET Communications*, Vol. 5, 2011, pp. 612-619.

10. L. Chen, W. Chen, X. Zhang, and D. Yang, "Analysis and simulation for spectrum aggregation in LTE-advanced system," in *Proceedings of IEEE Vehicular Technology Conference*, 2009, pp. 1-6.
11. L. Liu, M. Li, J. Zhou, X. She, L. Chen, Y. Sagae, and M. Iwamura, "Component carrier management for carrier aggregation in LTE-advanced system," in *Proceedings of IEEE Vehicular Technology Conference*, 2011, pp. 1-6.
12. H. Wang, C. Rosa, and K. Pedersen, "Performance analysis of downlink inter-band carrier aggregation in LTE-advanced," in *Proceedings of IEEE Vehicular Technology Conference*, 2011, pp. 1-5.
13. C. Li, B. Wang, W. Wang, Y. Zhang, and X. Chang, "Component carrier selection for LTE-A systems in diverse coverage carrier aggregation scenario," in *Proceedings of IEEE International Symposium on Personal Indoor and Mobile Radio Communications*, 2012, pp. 1004-1008.
14. H. Li, Y. Yu, B. Wang, W. Wang, and Y. Zhang, "Hierarchy based component carriers selection in carrier aggregation for LTE-A system," in *Proceedings of IEEE International Symposium on Personal Indoor and Mobile Radio Communications*, 2013, pp. 2679-2683.
15. R. Kwan, C. Leung, and J. Zhang, "Proportional fair multiuser scheduling in LTE," *IEEE Signal Processing Letters*, Vol. 16, 2009, pp. 461-464.
16. N. Guan, Y. Zhou, L. Tian, G. Sun, and J. Shi, "QoS guaranteed resource block allocation algorithm for LTE systems," in *Proceedings of IEEE International Conference on Wireless and Mobile Computing*, *Networking and Communications*, 2011, pp. 307-312.
17. M. E. Aydina, R. Kwana, and J. Wub, "Multiuser scheduling on the LTE downlink with meta-heuristic approaches," *Physical Communication*, Vol. 9, 2013, pp. 257-265.
18. Y. C. Wang and S. Y. Hsieh, "Service-differentiated downlink flow scheduling to support QoS in long term evolution," *Computer Networks*, Vol. 94, 2016, pp. 344-359.
19. Y. C. Wang and Y. C. Tseng, "Packet fair queuing algorithms for wireless networks," *Design and Analysis of Wireless Networks*, Nova Science Publishers, NY, 2005.
20. N. Guan, Y. Zhou, L. Tian, G. Sun, and J. Shi, "Utility maximization in LTE-advanced systems with carrier aggregation," in *Proceedings of IEEE Vehicular Technology Conference*, 2011, pp. 1-5.
21. X. Cheng, G. Gupta, and P. Mohapatra, "Joint carrier aggregation and packet scheduling in LTE-advanced networks," in *Proceedings of IEEE Conference on Sensor*, *Mesh and Ad Hoc Communications and Networks*, 2013, pp. 469-477.
22. H. S. Liao, P. Y. Chen, and W. T. Chen, "An efficient downlink radio resource allocation with carrier aggregation in LTE-advanced networks," *IEEE Transactions on Mobile Computing*, Vol. 13, 2014, pp. 2229-2239.
23. M. Lauridsen, H. Wang, and P. Mogensen, "LTE UE energy saving by applying carrier aggregation in a HetNet scenario," in *Proceedings of IEEE Vehicular Technology Conference*, 2013, pp. 1-5.
24. S. B. Lee, S. Choudhury, A. Khoshnevis, S. Xu, and S. Lu, "Downlink MIMO with frequency-domain packet scheduling for 3GPP LTE," in *Proceedings of IEEE International Conference on Communications*, 2009, pp. 1269-1277.

25. T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein, *Introduction to Algorithms*, The MIT Press, London, 2009.
26. F. Zarai, K. B. Ali, M. S. Obaidat, and L. Kamoun, "Adaptive call admission control in 3GPP LTE networks," *International Journal of Communication Systems*, 2012, pp. 1-13.
27. P. Kela, J. Puttonen, N. Kolehmainen, T. Ristaniemi, T. Henttonen, and M. Moisio, "Dynamic packet scheduling performance in UTRA long term evolution downlink," in *Proceedings of IEEE International Symposium on Wireless Pervasive Computing*, 2008, pp. 308-313.



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