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Downlink Resource Allocation for Enhanced Inter-Cell Interference Coordination (eICIC) in Heterogeneous Cellular Networks

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ABSTRACT

LTE network architectures frequently make use of both macrocells and small cells (e.g., micro-, pico-, or nanocells) to allocate resources in an optimal manner to serve the exponentially increasing traffic load of mobile users. These heterogeneous networks (HetNets) must jointly consider the dynamic load on the network and the relative spatial distances and corresponding channel qualities of potentially mobile users. In this paper, we develop a modified downlink resource allocation model in order to jointly reduce the inter-cell interference and maximize the throughput of HetNets. First, we propose an efficient approach to optimize resource allocation for three representative LTE user types. We then compare our run-time performance to two other mathematical methods. Next, we extend our model to more complex networks and solve the resource allocation problem via convex optimization. We simulate HetNet scenarios in order to display optimization variables' solution space under different user type ratios and compare against two typical frameworks under varying numbers of small cells. Lastly, our proposed model is compliant with the eICIC standard while achieving better performance than previously proposed techniques.

Keywords: LTE, eICIC, resource allocation, HetNets, macrocells, small cells

I. INTRODUCTION

With the bandwidth needs of mobile users exploding in recent years, cellular operators have increasingly deployed small cells alongside of macrocells to inject capacity into LTE Networks. These LTE-Advanced heterogeneous networks (HetNets) operate by having small cell base stations with lower power and smaller coverage areas inside the larger coverage area of deployed macrocell base stations. These small cell base stations are usually deployed in places with high user equipment (UE) density where data traffic can be offloaded to these small cell systems [1]. In order to combat the HetNet interference, the concept of enhanced inter-cell interference coordination (eICIC) from LTE Release 10 provides a potential approach to reduce inter-cell interference and improve the network throughput by introducing the low-power Almost Blank Subframes (ABS) [2]. In downlink channels, macrocell base stations only transmit low power reference signals during the ABS periods, over which the small cell base station can transmit data to its associated UEs with less interference due to muted periods introduced by these ABSs [3]. Chen et al. proposed a method jointly optimizing ABS power allocation and resource allocation [4]. Deb et al. proposed a formal framework for ABS optimization and UE association [5]. They also performed extensive evaluation on a real LTE deployment map. A simple ABS ratio allocation method was used by Lembo et al. to maximize network throughput based on parameters estimated directly from the network [9].

In this paper, to the best of our knowledge, ours is the first work to propose a double-ratio dynamic solution, which is standards compliant in its use of ABS periods in LTE Release 10. Three representative types of UEs are governed by association rules under different situations and their received signal to interference plus noise ratio (SINR) expressions are described. First, we derive the optimization model analytically by implementing the proposed approach for a common simple structure and solve it with a derivative search, which is efficient and easy to implement. We then extend our model to more complex structures that contain multiple small cells. Next, we apply convex optimization to compute the system parameters that contribute to the resource allocation strategy and display the optimization variables solution space under different user type ratios. At last, the proposed approach is evaluated via simulation for practical HetNet scenarios which take into consideration practical factors, such as propagation, topological features, base station parameters, and user location. Simulation results show that our approach can increase throughput by up to 13% compared with the standard eICIC and up to 48% compared with traditional macrocell-only structures. We visually represent the solution spaces to generalize the optimization as much as possible based on different UE ratios for HetNets with one or two small cell base stations. With the flexibility brought by double ratios, the approach is particularly well suited for practical situations with high UE density under small cell coverage, with a combination of many users and high traffic demands common to conferences, office buildings, shopping malls, hotels, and multi-family residential environments.

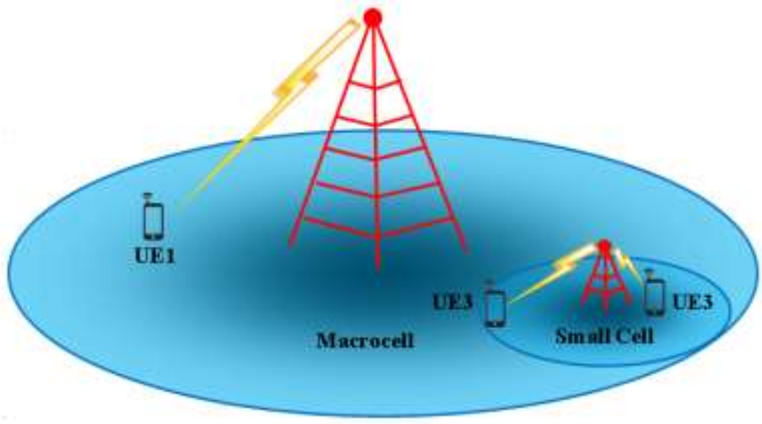


Fig. 1. Basic HetNet structure with one macrocell base station and one small cell base station. Within the macrocell ABS periods, the UE3 would communicate over the small cell with improved SINR.

II. NETWORK MODEL

A. Association

In a simple LTE-A HetNet structure that consists of one macrocell and one small cell, the macrocell's coverage region is significantly greater than that of the small cell due to its high transmission power and being physically mounted at a far greater height. We define three representative types of user equipment (UE) scenarios for the HetNet structure based on the relative positioning from the two base stations (shown in Fig. 1). On one extreme, UE1 is located in the coverage area of the macrocell but is far away from small cell coverage area. Therefore, UE1 should associate with the macrocell base station. On the other extreme, UE2 is well within the coverage area of small cell. As a result, UE2 usually attains higher SINR from the small cell base station as compared to the macrocell base station. Therefore, UE2 should always associate with the small cell. In between these two extremes, UE3 is positioned on the edge of the coverage region of the small cell but well within the coverage area of the macrocell. Hence, the main challenge for UE3 is the inter-cell interference caused by the radio transmission of the macrocell base station. Since UE3 receives a comparatively weaker signal from the small cell base station and stronger interference from the macrocell base station, it is very likely to have poor downlink data rate performance, especially when it is associated with the small cell. To address the difficulty of the UE3 association problem, Cell Selection Bias (CSB) has been proposed by the LTE standard [5]. It introduces a bias before applying the association rules to UE3 so that the small cell is always the preferred association station. In this work, we consider a potential UE *u* is associated with small cell *i* when:

$$\max_{i \in S}\left\{P_{small,i}^{normal} + b_i\right\} > P_{design} \tag{1}$$

Here, $P_{small,i}^{normal}$ and P_{design} are the received signal power from the small cell *i* and association threshold, respectively. The term, b_i, is the designed bias favorable to the small cell *i*. Otherwise, association should belong to the macrocell.

B. Double-Ratio Approach

Assuming all users strictly follow the association rules, we now consider the resource allocation optimization using two ratios to address the problem. The LTE standard defines an *ABS ratio,* which is the fraction of time that the ABS period is assigned to UE3 (edge user) by the macrocell over a complete frame. We introduce a new ratio called the *normal ratio,* which represents the fraction of normal subframes assigned to UE3 by the small cell out of all subframes in a complete frame when macrocell does not transmit ABS (i.e., when normal subframes will be transmitted). Note that both ratios deal with the resource allocation out of the total subframes (number of *N*) in a single frame. How these two ratios contribute to resource allocation in a complete frame is further shown in Fig. 2. Both ratios deal with resource allocation according to UE3, but the *ABS ratio* reflects the resource allocation implemented by the macrocell, while the *normal ratio* is governed by small cell. The introduction of the *normal* *ratio* has no influence on the current ABS standard because it is strictly confined to the small cell's behavior. On the other hand, when combined with the *ABS ratio*, it further improves the small cell users' data performance by creating more flexible resource allocation methods, especially suitable for small cells with relevancy to both UE2 and UE3 user types.

C. SINR

Consider a HetNet scenario with one macrocell and S small cells. The SINR expressions for UE1 and UE2 associated with the small cell *i* give:

$$C_{UE1}(u) = \frac{P_{macro}^{normal}(u)}{\sum_i^S P_{small,i}^{normal}(u) + N_0} \tag{2}$$

$$C_{UE2}(u) = \frac{P_{small,i}^{normal}(u)}{\sum_{k\neq i}^S P_{small,k}^{normal}(u) + P_{macro}^{normal}(u) + N_0} \tag{3}$$

Here, u represents any licensed user that belongs to one of three UE types. $P_{macro}^{normal}(u)$ denotes the received power from the macrocell to UE u with normal subframes transmissions, and $P_{small,i}^{normal}(u)$ represents power received from small cell *i*. Lastly, N_0 is the AWGN power.

Due to the ABS implemented by the macrocell base station and introduction of the normal ratio, there are two scenarios that could be relevant to UE3:

1) The small cell communicates with UE3 when the macrocell is transmitting ABS frames. In this case, UE3 gains improved SINR since the macrocell base station remains muted.

$$C_{UE3}(u) = \frac{P_{small,i}^{normal}(u)}{\sum_{k\neq i}^S P_{small,k}^{normal}(u) + P_{macro}^{ABS}(u) + N_0} \tag{4}$$

2) The small cell communicates with UE3 when the macrocell base station is transmitting normal subframes. In this case, UE3 has low SINR received because macrocell is transmitting high power normal subframes.

$$C_{UE3}(u) = \frac{P_{small,i}^{normal}(u)}{\sum_{k\neq i}^S P_{small,k}^{normal}(u) + P_{macro}^{normal}(u) + N_0} \tag{5}$$

Hence, we have $P_{macro}^{ABS}(u) < P_{macro}^{normal}(u)$. Received power information can be easily collected in HetNets. The average PHY data rate, denoted by $R_1, R_2, R_3^{ABS}, R_3^{normal}$ respectively, are derived by either looking up to LTE rate table or employing the maximum information capacity expression:

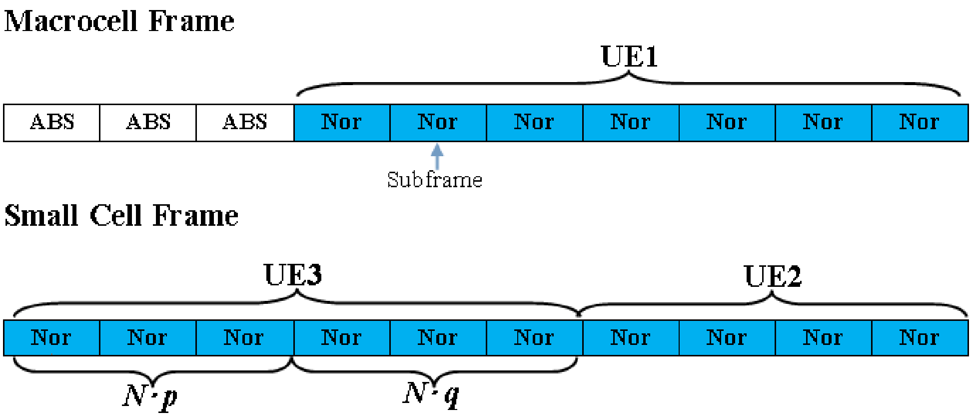
$$R(u) = log_2(1 + C(u)) \tag{6}$$

Here, *R(u)* is the maximum information rate per Hz, and *C(n)* represents the SINR expression (2) (3) (4) (5). With enough knowledge about association and each UE's SINR, we are able to calculate the whole throughput.

D. Resource Allocation

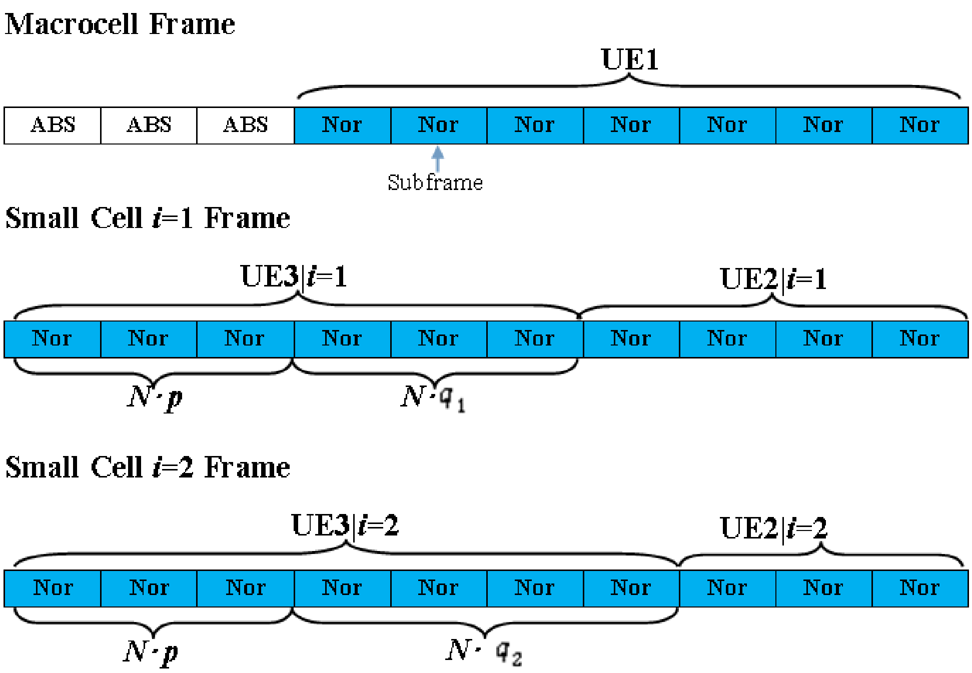
Two synchronous TDM LTE frames (belonging to the macrocell and small cell, respectively) are shown in Fig. 2(a). We describe the resource allocation problem in a simple structure, both of which consists of N subframes. The problem is how to allocate these subframes to maximize throughput. In this work the double ratios, including the ABS ratio and normal ratio are discussed, denoted by *p* and *q*, respectively. In practice, ABS and normal subframes assigned to each UE type are randomly distributed in a complete frame. However, for mathematical analysis, it is feasible to analyze resources in sequential order without loss of generality.

Clearly, resources that UE3 attains from the small cell base station are given as *(N·p+N·q)*; the remaining small cell frame resources will be given to UE2, denoted by *(N-N·p-N·q)*. On the other hand, UE1, who is associated with macrocell, will always be given normal subframes from macrocell, denoted by *(N-N·q)*. The selection of *p* and *q* will determine the general allocation of frame resources on both the macrocell and small cell and further influence the aggregate HetNet throughput. This protocol can be easily extended to HetNets with multiple small cell base stations.



(a) Simple structure resource allocation

(b)



(b) Complex structure resource allocation

Fig. 2. Frame structure and resource allocation description.

III. MODEL NUMERIC ANALYSIS

In this section, we forumalte the optimation problem in terms of system throughput. The ABS and normal ratio are obtained by using analysis from a typical and common HetNet structure with one macrocell and one small cell containing typical UEs that have been previously discussed. Assuming U_1 represents the set of users that belongs to UE1 associated with the macrocell base station and set U_2 represents the set of users of type UE2 associated with the small cell base station. Similarly, we have defined user set U_3 for type UE3, which might suffer from interference from the macrocell depending on whether macrocell is transmitting ABS or normal frames. The information rates of $R_1, R_2, R_3^{ABS}, R_3^{normal}$ are derived from expression (6), respectively.

A. Simple Structure

Simple structures are the most typical and common network model, with only one macrocell and one small cell. Given each UE, resource allocation details based on the ABS ratio p and normal ratio q, considering OFDMA subcarriers in LTE, the optimization problem is to maximize the proportional fairness function in a single frame such that:

$$\begin{aligned} T = & \sum_{u \in U_1} \ln\big((N - N \cdot p) \cdot R_1(u)\big) \\ & + \sum_{u \in U_2} \ln\big((N - N \cdot p - N \cdot q) \cdot R_2(u)\big) \\ & + \sum_{u \in U_3} \ln\left(N \cdot p \cdot R_3^{ABS}(u) + N \cdot q \cdot R_3^{normal}(u)\right) \\ & \text{s.t.} \quad 0 \le p \le 1, 0 \le q \le 1, 0 \le q + p \le 1; \end{aligned} \tag{7}$$

We propose an efficient approach named *iteratively search* in order to compute p and q. The partial differential equation $\frac{\partial T}{\partial q} = 0$ gives:

$$q = \frac{(1-p)U_3 R_3^{normal} - pU_2 R_3^{ABS}}{(U_3 + U_2)R_3^{normal}} \tag{8}$$

$$s.t. \quad 0 \le p \le \frac{U_3 R_3^{normal}}{U_3 R_3^{normal} + U_2 R_3^{ABS}} \le 1; \tag{9}$$

Constraint (9) must ensure the normal ratio q to be intervally meaningful. Therefore, the search of p and q can be programmed according to the algorithm below:

```
Caculate p_max using constraint (8);
Initialization p = 0.001 ;
while p < p_max do
        Caculate q using equation (7);
        Caculate T using q, p;
        p= p+0.001.
end
Find p,q when T = max(T).
```

Algorithm: iteratively search

Expression (8) gives the value of q, supposing the value p is known. By depicting the value of fairness function (6) based on step-increasing p, we are able to find the optimal solution. One example to find p, q for 100 UEs' HetNet is shown in Fig. 3.

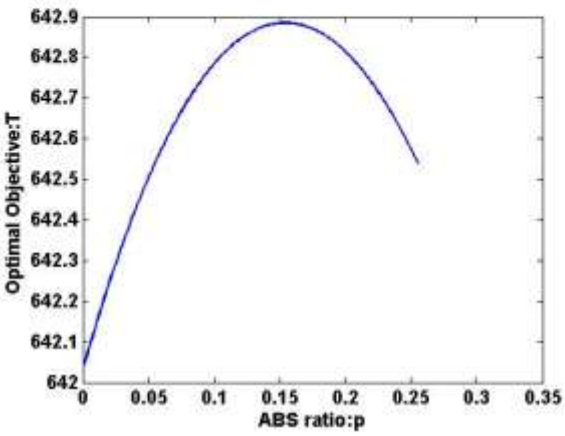


Fig. 3. Depicting values of optimal objective based on increasing p in order to find the optimal solution. The figure shows the maximum result of objective around 632.87 log(bits)/frame when p is step-wise increasing. This example shows p=0.1540, q=0.1987 when the optimal results exist.

In order to perform the computational complexity analysis, 10 different fairness objectives based on various UE association information are solved using proposed algorithm, convex optimization [6] and Monte Carlo method [7], respectively. With convex optimization, the problem is formulated and solved by CVX [8] Monte Carlo method, we increase p and q continuously to calculate the function, and the maximum value will be kept. Unless all possible cases can be traversed, there is no guarantee of finding the optimal value. The method comes to a stop when an approximate optimal value is found (error < 1%). All three methods are realized by MATLAB in a state-of-the-art notebook (i5 2.6GHz, 8G DDR3 RAM), and the run-time is simulated to give the method performances, as shown in Table I.

TABLE I. RUN-TIME(SECOND) FOR THREE METHODS

Simulation Index	Iteratively Search	Convex Optimization	Monte Carlo
1	0.298271	14.011817	12.180776
2	0.252928	13.756312	11.259193
3	0.311425	13.863814	4.327781
4	0.207103	13.205385	16.399021
5	0.402704	14.664734	3.466252
6	0.340676	15.122006	21.530664
7	0.248521	14.578271	14.599079
8	0.375830	15.483856	7.665991
9	0.311448	13.818306	4.722019
10	0.273473	13.325017	7.143678
Average	0.3022	14.1830	10.3294

Our method, which jointly uses the concept of step search and derivativef, reduces more time while still the optimization solutions for a simple HetNet structure. Because only the integral number of subframes is employed in practice, deviation can be tolerated to a certain extent, based on the search step. Our proposed algorithm takes this advantage to significantly save computation time.

B. Complex Structure

Extend the simple HetNet structure to cases where there are multiple small cells, the number of which is denoted by S. The frame structure is shown in Fig. 2(b), where p is the ABS ratio of main macrocell, but q will vary depending on the small cell. In other words, the normal subframes ratio allocated to UE3 differs among the small cells. SINR for type UE3 should allow for the interference from small cells. Assume that each small cell serves set U_{2i} defined by type UE2, and set U_{3i} of type UE3 normal ratio q_i (i=1,2,...,S). The fairness function for complex HetNet gives:

$$
\begin{aligned}
T = & \sum_{u\in U_1} \ln\big((N - N\cdot p)\cdot R_1(u)\big) \\
& + \sum_{i=1}^{S}\sum_{u\in U_{2i}} \ln\big((N - N\cdot p - N\cdot q_i)\cdot R_2(u)\big) \\
& + \sum_{i=1}^{S}\sum_{u\in U_{3i}} \ln\left(N\cdot p\cdot R_3^{ABS}(u) + N\cdot q_i\cdot R_3^{normal}(u)\right) \qquad (10) \\
& \text{s.t.}\quad 0 \le p \le 1, 0 \le q_i \le 1, 0 \le q_i + p \le 1;
\end{aligned}
$$

Clearly, the convex/Monte Carlo approach is not proper for solving more than two optimization variables. Because the objective function is still concave, CVX is applied again to solve the problem using disciplined convex programs, an approach called the successive approximation method is proposed to allow the primal or dual solvers to solve exponential functions [8].

IV. SIMULATION AND DISCUSSION

In this section, the performance of LTE-A HetNet sector structure is evaluated and shown in Fig. 4. Parameters for the simulation model are based on the 3GPP LTE-A HetNet framework [3]. Suppose the carrier frequency is 2 GHz, and the macrocell has an inter-site distance (ISD) of 500 m. The transmission EIRP of the macrocell and small cell are 46 dBm and 20 dBm, respectively. We assume that the base station employs the full buffer so that frame transmission are continuous. The complete frame length is *N*=100. To isolate the effects of our approach, we assume the CRS macrocell interference is perfectly canceled [9]. The small cell has an inter-site distance of 110 meters. UEs are randomly distributed within the coverage area of macrocell. Also, association rules are applied to distinguish UE1, UE2 and UE3.

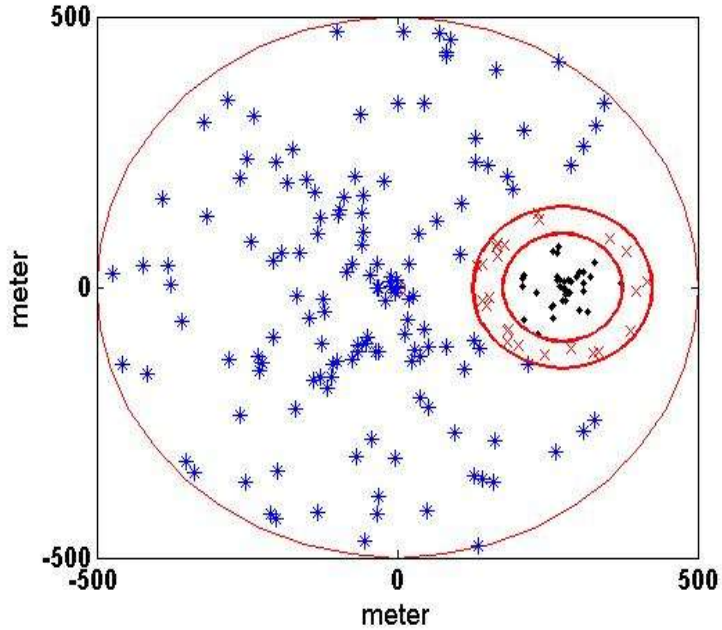


Fig. 4.   Simple structure with 200 UEs. Circles display the assosiation rules.

Firstly, for simplicity, the free space channel path loss model is applied to calculate the received power for each UE: $L = 20log_{10}(\frac{4\pi}{d})$, where L is the path loss, and d is the distance from station to user. The physical dimensions of the base stations and users are ignored. Then, information data rates can be directly computed by [6]. UEs are randomly distributed, and association is completed to three UE types. At last, we solve the HetNet resource allocation problem for simple structures with proposed search algorithm and by the convex optimization technique in complex HetNet structures. Throughput subject to the fairness objective is computed under the three frameworks respectively: macrocell without small cells, macrocell with standard eICIC, and the proposed approach. The macrocell without small cells only provides service to users via the macrocell. The macrocell with standard eICIC only employs an optimized *ABS ratio* to reallocate subframe resources. Note that the concept of relative throughput is more meaningful for the performance discussion among different networks.

Fig. 5 and Fig. 6 show the optimization parameters intuitively under various user type ratios and given certain *N*. Here, the *UE2 ratio* means the proportion of users that belongs to UE2 out of *N* in small cell *i*. Similarly, the *UE3 ratio* means the proportion of users that belongs to UE3 out of *N* in small cell *i*. Fig. 5 shows the optimization solutions based on the simple structure with one small cell solved by our convex approach. Fig. 6 is based on the our concave approach for complex HetNet structures with two small cells (*i*=1,2). The two small cells are configured to have same number of users but with randomly distributed positions. We see that the *UE3 ratio* and *UE2 ratio* jointly influence the resource allocation strategies (p and q_i). Specifically, *UE2 ratio* plays a dominant role in adjusting the value of *p*, while the *UE3 ratio* leads to a major influence on the value of *q*. The network tends to favor UE3 when both *UE3 ratio* and *UE2 ratio* are high, but the preference will turn to UE2 when both *UE3 ratio* and *UE2 ratio* are low. Although Fig. 6(b) and Fig. 7(c) have similar images, there is still a slight difference due to spatial differences. By building the optimization variable graphs beforehand, the best resource allocation strategy to a specific network can be found quickly with the knowledge of UE association information.

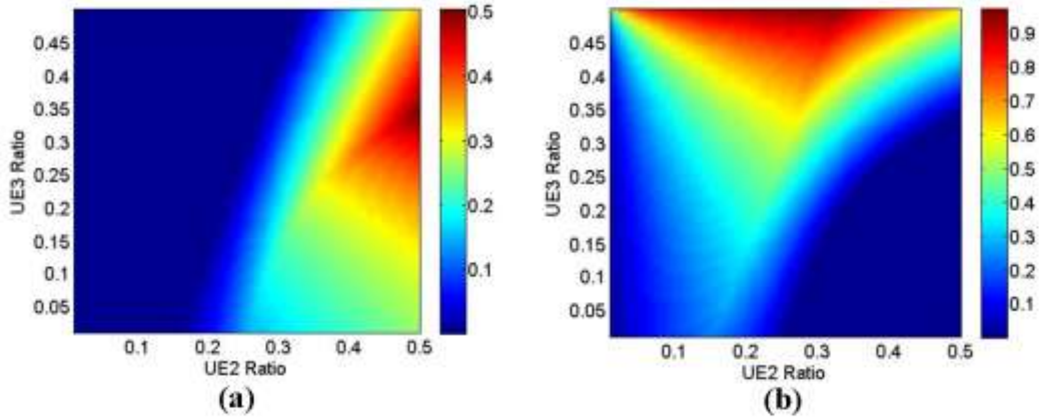


Fig. 5. Optimization variables in simple structure: (a) p (b) q

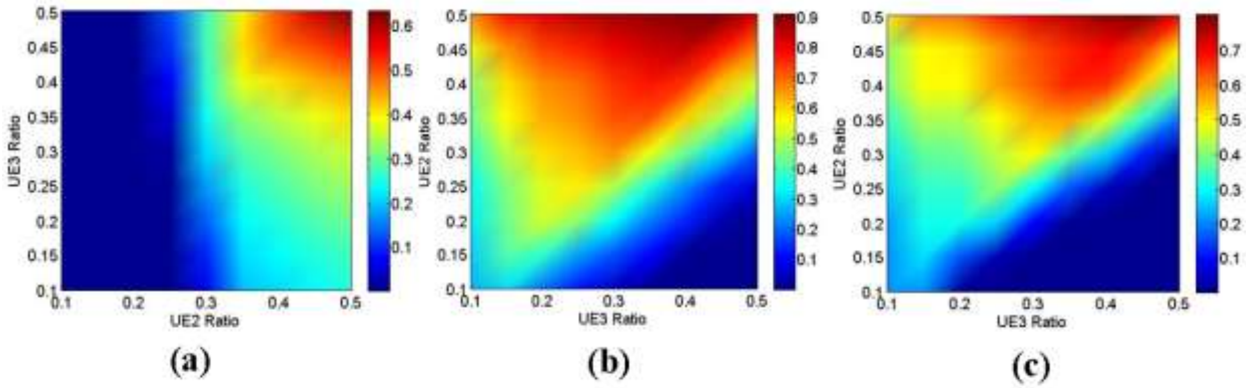


Fig. 6. Optimization variables in complex structure: (a) p (b) q_1 (c) q_2

Fig. 7 shows the normalized throughput between three frameworks with a varying number of UEs for a simple structure. Normalization is achieved by dividing the least value of throughput (macrocell without eICIC when *N*=100). It can be observed that our approach could achieve higher throughput than the other two frameworks as additional UEs achieve a greater advantage (13.2% increasing compared with standard eICIC and 47.9% compared with single macrocell). Fig. 8 shows the normalized throughput between the three frameworks with a changing number of small cells. It is demonstrated that the proposed double-ratio approach achieves better throughput performance compared to macrocells with a standard use of ABS frames as the number of small cells increases. Note that throughput tends not to increase constantly due to the practicalities of association.

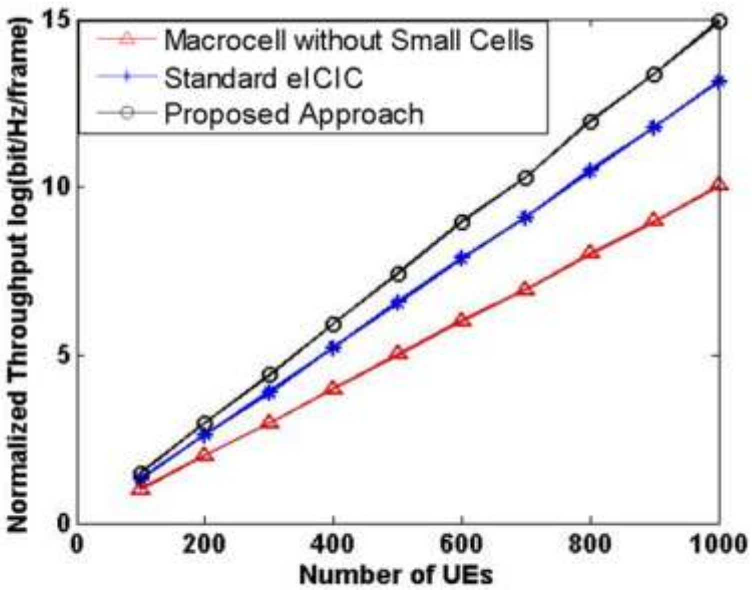


Fig. 7. Normalized throughput (log information rate/frame) for simple structure with a varying number of UEs.

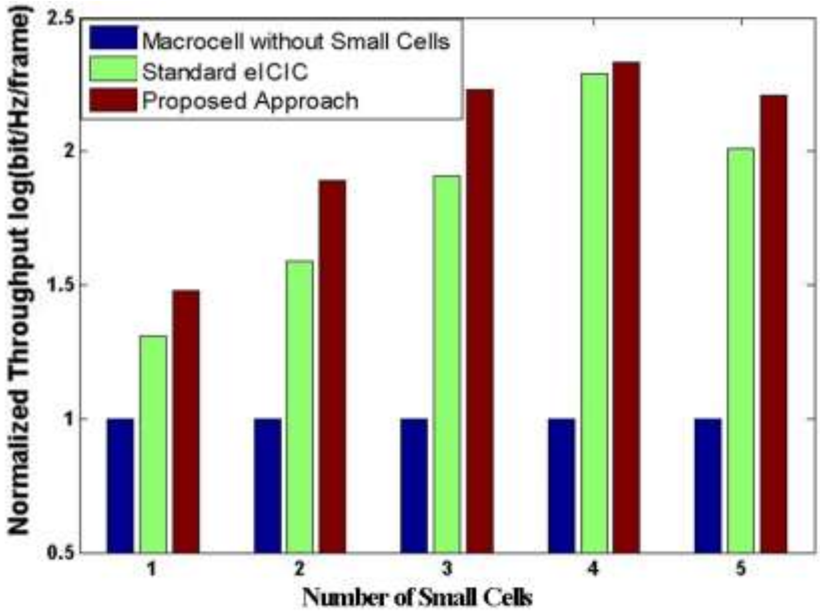


Fig. 8. Normalized throughput (log information rate/frame) for the complex HetNet structure with a varying number of small cells

V. CONCLUSION

In this paper, a modified downlink resource allocation approach is proposed to optimize the HetNet problem by introducing two different ratios. By comparing with convex optimization and Monte Carlo, we can show that our proposed efficient algorithm to solve the optimization variables saves time and is easy to implement, for simple HetNet structures. A disciplined convex optimization framework is implemented to solve the more complex structures. Simulation results are based on practical LTE HetNet parameters where we display the solution space of optimization variables and compare the proposed approach with two other typical frameworks. Finally, we find that the proposed approach is compliant with standard ABS and provides better flexibility for resources allocation while achieving better throughput.

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