A Minimum Data-Rate Guaranteed Resource Allocation With Low Signaling Overhead in Multi-Cell OFDMA Systems

Hojoong Kwon, Won-Ick Lee, and Byeong Gi Lee

Abstract: **In this paper, we investigate how to do resource allocation to guarantee a minimum user data rate at low signaling overhead in multi-cell *orthogonal frequency division multiple access* (OFDMA) wireless systems. We devise *dynamic resource allocation* (DRA) algorithms that can minimize the QoS violation ratio (i.e., the ratio of the number of users who fail to get the requested data rate to the total number of users in the overall network). We assume an OFDMA system that allows dynamic control of *frequency reuse factor* (FRF) of each sub-carrier. The proposed DRA algorithms determine the FRFs of the sub-carriers and allocate them to the users adaptively based on inter-cell interference and load distribution. In order to reduce the signaling overhead, we adopt a hierarchical resource allocation architecture which divides the resource allocation decision into the *inter-cell coordinator* (ICC) and the *base station* (BS) levels. We limit the information available at the ICC only to the load of each cell, that is, the total number of sub-carriers required for supporting the data rate requirement of all the users. We then present the *DRA with limited coordination* (DRA-LC) algorithm where the ICC performs load-adaptive inter-cell resource allocation with the limited information while the BS performs intra-cell resource allocation with full information about its own cell. For performance comparison, we design a centralized algorithm called *DRA with full coordination* (DRA-FC). Simulation results reveal that the DRA-LC algorithm can perform close to the DRA-FC algorithm at very low signaling overhead. In addition, it turns out to improve the QoS performance of the cell-boundary users, and achieve a better fairness among neighboring cells under non-uniform load distribution.**

Index Terms: **Dynamic resource allocation, inter-cell interference, orthogonal frequency division multiple access (OFDMA), quality of service (QoS), signaling overhead.**

I. INTRODUCTION

Future wireless communication systems are required to provide high data-rate and high *quality of service* (QoS) to multiple users, while using minimal resources of bandwidth and transmission power. One of the most promising multiple access techniques to meet this stringent requirements turned out to be the *orthogonal frequency division multiple access* (OFDMA) [1]–[3]. The spectral efficiency of the OFDMA systems can be further enhanced by employing adaptive resource allocation techniques. So the issue of resource allocation has been widely studied for the OFDMA systems, yet mostly dealing with isolated-cell scenarios [4]–[8].

The main problem that arises in resource allocation in multi-cell environments is the management of the inter-cell interference. It can be effectively handled by dynamic channel allocation. There have been reported a number of algorithms on *dynamic channel allocation* (DCA) [9] but the conventional DCA algorithms have some limitations: First, the conventional DCA algorithms were designed to ensure that the *signal-to-interference plus noise ratio* (SINR) at each receiver is above the required value, which is fixed regardless of the channel condition for voice services. However, future data wireless systems are expected to employ *adaptive modulation and coding* (AMC) schemes to exploit the time-varying nature of wireless channels [10]–[12]. The AMC scheme makes it possible to control the transmission data rate according to the SINR without requiring to maintain a minimum SINR level. Secondly, the conventional DCA algorithms were targeted at the *code division multiple access* (CDMA) and/or *time division multiple access* (TDMA) systems, whose resource structures are different from that of the OFDMA system. The OFDMA system provides multiple sub-channels that experience different inter-cell interferences. This structure allows for a high degree of flexibility for avoiding inter-cell interference.

Recently, a resource allocation algorithm for multi-cell OFDMA systems was reported in [13], which aimed at maximizing the total throughput over the whole network but without considering the QoS requirements. In this case, however, it tends to allocate most resources to the users with better channel conditions, thus resulting in unfair resource allocation. It causes a structural problem in the multi-cell environments in that the users located near the center of a cell usually get good channels which are hardly affected by inter-cell interference, whereas the users located at the cell boundary usually get bad channels which are likely to deteriorate by both large path loss and high inter-cell interference. So the QoS of the users at the cell-boundary becomes an important performance criterion in multi-cell networks. Therefore it is very much demanding to devise efficient inter-cell resource allocation schemes that can improve the QoS of the cell-boundary users.

In this paper, we present a resource allocation algorithm that can guarantee a minimum level of data rate even to the users who are located at the cell boundary of multi-cell OFDMA systems.

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The algorithm, called *dynamic resource allocation* (DRA) algorithm, is designed to minimize the *QoS violation ratio*, which refers to the ratio of the number of users who fail to get the requested data rate to the total number of users in the overall network. In support of this, we take the approach of dynamically controlling the value of the *frequency reuse factor* (FRF) of each sub-carrier, allocating the sub-carriers with FRF 1 to the users getting small inter-cell interference and the sub-carriers with high FRF 3 (or 4) to the users getting high inter-cell interference. We also take advantage of the fact that the load distribution is not uniform, in general, in the network, therefore allocating the sub-carriers with high FRF according to the load conditions of the cells. This arrangement enables to improve the fairness not only among the users in the same cell but also among the users in different neighboring cells.

In addition, we present a practical method that can realize the DRA algorithm with low signaling overhead. In handling the inter-cell interference among multiple cells, signaling overheads are inevitably induced while coordinating the relevant cells, which is likely to forbid a good resource allocation algorithm to be practical. We present a limited coordination DRA (namely DRA-LC) algorithm that reduces the signaling overhead substantially by limiting the information exchange among the relevant cells. The architecture of the DRA-LC algorithm is similar to that of the algorithm developed in [13] in that the resource allocation decision is divided into the *inter-cell coordinator* (ICC) and the *base station* (BS) levels but is much different in the signaling overhead. The signaling overhead is much smaller for the DRA-LC as we limit the signaling information to the total number of sub-carriers required for supporting the data rate requirement of all the users. For performance comparison, we also develop a centralized algorithm called the *DRA with full coordination* (DRA-FC) algorithm.

The rest part of the paper is organized as follows: We first describe the system model in Section II. Then, we formulate the optimization problem for the resource allocation and introduce the resource allocation architecture in Section III and present the DRA-FC algorithm in Section IV. In Section V, we study how to reduce the signaling overhead for the inter-cell coordination and introduce the DRA-LC algorithm. Finally, we present numerical results on the performance of DRA-LC, in comparison with that of DRA-FC, in Section VI.

II. SYSTEM MODEL

We consider a sectorized cellular system with each cell composed by N_s sectors. We assign a label $(1, 2, \cdots, N_s)$ to each sector as shown in Fig. 1. We assume an ideal sectorization with no intra-cell interference. We assume that the system allows to dynamically control the FRF on a sub-carrier basis. We consider two values of FRF, 1 and N_s.[1] When FRF is N_s, a sub-carrier is utilized only by one sector among every N_s sectors belonging to different cells. In this case, we define a *pseudo-cell* to be the cluster of adjacent N_s sectors within which each sub-carrier is not reused, resulting in avoiding the inter-cell interference among the constituent sectors. On the other hand, when FRF is 1, a sub-carrier is reused by all the sectors. Fig. 1 shows the exemplary definitions of the pseudo-cell for hexagonal and rectangular systems, respectively. Fig. 2 illustrates the exemplary frequency reuse patterns in the hexagonal system.

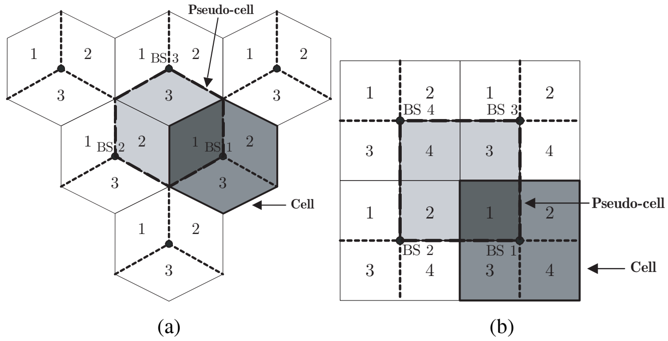

Fig. 1. Definition of "pseudo-cell" in sectorized cellular system: (a) Hexagonal systems and (b) rectangular systems.

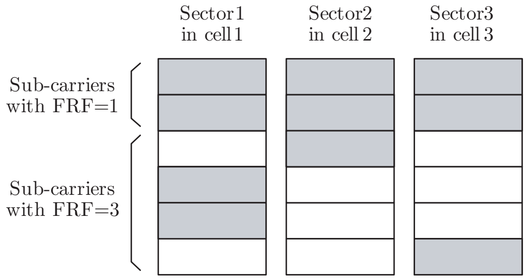

Fig. 2. Illustration of frequency reuse patterns in hexagonal system. (The shadowed sub-carrier represents that the corresponding sector uses the sub-carrier for data transmission.)

The entire network is partitioned into multiple pseudo-cells. For each pseudo-cell, a dynamic resource allocation algorithm determines whether the FRF of each sub-carrier is set to 1 or 3, and which sector utilizes the sub-carriers with FRF = 3 exclusively. The inter-cell interference of a user within a particular pseudo-cell depends on the resource allocation in other pseudo-cells. So in order to optimize the overall network performance, it is necessary to determine the resource allocation of all the pseudo-cells simultaneously in a centralized fashion. However, it is not practical to include all the pseudo-cells in the optimization especially in large scale wireless networks. Computation for sub-carrier allocation becomes overly complicated and, in addition, it requires a high level of coordination among the constituent cells to exchange information. In order to make the solution realistic, we choose to determine the resource allocation of each pseudo-cell independently, instead. We manage the inter-cell interference among the sectors within each pseudo-cell only, noting that the sectors within each pseudo-cell are potentially mutual dominant-interfering sectors. Such an independent operation among different pseudo-cells makes it difficult to predict exactly the inter-cell interference from the sectors outside the corresponding pseudo-cell. So we assume the worst-case interference in resource allocation, which happens when the FRFs of all the other pseudo-cells are set to 1. Assuming that the same resource allocation algorithm is applied to each pseudo-cell, we focus on one pseudo-cell in the following. We will use

[1] In this paper, we consider only two FRF values for simplicity, but it may be extended to the cases of multiple FRF values.

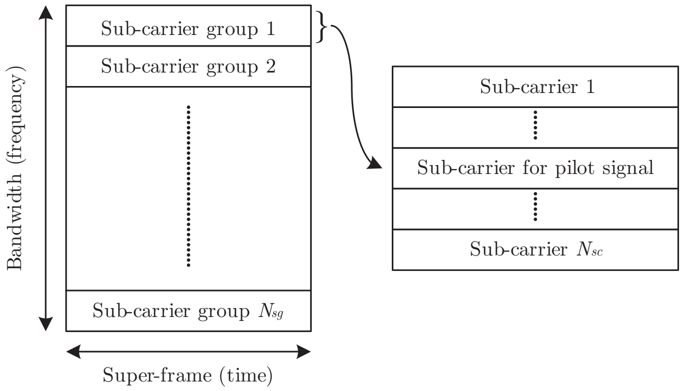

Fig. 3. Radio resource structure in frequency-time domain.

the term 'cell' instead of 'sector' to emphasize that different sectors within the pseudo-cell belong different cells.

In broadband wireless OFDM systems, the channel condition on each sub-carrier varies due to frequency selective fading. However, within the range of coherent bandwidth, the difference of the channel conditions among the constituent sub-carriers may be regarded negligible. So we group the sub-carriers within a coherent bandwidth range as a *sub-carrier group* (SG). Then, the radio resource structure takes the shape shown in Fig. 3. We may assume that the SINR value is identical among all the sub-carriers belonging to one SG. The overhead needed for feeding back the channel condition reduces significantly if it is done SG based. We assume that each SG consists of N_{sc} data sub-carriers and one pilot sub-carrier as indicated in Fig. 3.

For dynamic resource allocation, it is required to collect the channel state information from the users. We assume that different BSs use different code signatures when broadcasting pilot signals. Then, each user can measure the received powers of the pilot signals coming from multiple BSs and calculate the SINRs for the both cases of FRF = 1 and N_s. When FRF = 1, the SINR of user j in SG i can be calculated by

$$\gamma_{ij}(1) = \frac{P_{ij(b)}}{\sum_{b' \in \mathbf{B}_j \setminus \{b\}} P_{ij(b')} + \sum_{b' \in \bar{\mathbf{B}}_j} P_{ij(b')} + W\eta} \tag{1}$$

where b is the index of the BS that user j is associated with, $\mathbf{B}_j$ the index set of the BSs constituting the pseudo-cell that user j belongs to, $\bar{\mathbf{B}}_j$ the complement of $\mathbf{B}_j$, $P_{ij(b)}$ the power of the signal that user j receives from BS b, W the total bandwidth, and η the power spectral density of the thermal noise. When FRF = N_s. the SINR is simplified to

$$\gamma_{ij}(N_s) = \frac{P_{ij(b)}}{\sum_{b' \in \bar{\mathbf{B}}_j} P_{ij(b')} + W\eta}, \tag{2}$$

since the term representing the interference from the neighboring sectors within user j's pseudo-cell is non-existent. As mentioned above, we use the worst-case value for the inter-cell interference from outside the pseudo-cell. Using the above equation, each user calculates the SINR in each SG for both FRF values and sends all the channel state information to the corresponding BS. The achievable data rate for the given SINR is determined by

$$R_{ij} = \frac{B}{N_{sg}(N_{sc}+1)} \log_2 \left(1 + \frac{\gamma_{ij}(\text{FRF})}{\Gamma}\right) \tag{3}$$

where B is the channel bandwidth, N_{sg} the number of SGs, and $\Gamma \equiv -\ln(5\text{BER})/1.5$ for the *bit error rate* (BER) requirement [11].

III. PROBLEM FORMULATION AND RESOURCE ALLOCATION ARCHITECTURE

We define some notations as follows: f_i denotes the FRF value of SG i; $R_{ij}(f_i)$ the achievable data rate of user j on SG i; n_{ij} the number of sub-carriers allocated to user j in SG i; $\mathbf{U}^k$ the index set of the users in cell k; $\mathbf{U}^{pc}$ the index set of the users in a given pseudo-cell (PC) (i.e., $\mathbf{U}^{pc} = \bigcup_k \mathbf{U}^k$); and $|\mathbf{A}|$ the number of elements in a set $\mathbf{A}$.

We assume that user j requires that the received data rate be no less than a particular value, Q_j^{req}, specified by the application. To meet this requirement, f_i and n_{ij} should be arranged to satisfy the inequality

$$\sum_{i=1}^{N_{sg}} n_{ij} R_{ij}(f_i) \ge Q_j^{req}. \tag{4}$$

As QoS violation occurs when the user requirement is not satisfied, we define the *QoS violation ratio* in the pseudo-cell as the ratio of the number of users whose requirements are not satisfied to the total number of users. Then, the QoS violation ratio is given by

$$\rho_{QoS} = \frac{1}{|\mathbf{U}^{pc}|} \sum_{j \in \mathbf{U}^{pc}} 1 \left(\sum_{i=1}^{N_{sg}} n_{ij} R_{ij}(f_i) < Q_j^{req} \right) \tag{5}$$

where $1(C)$ is an indicating functions that becomes 1 if condition C is met and 0 otherwise.

In terms of the QoS violation ratio, the goal of dynamic resource allocation may be said to minimize the QoS violation ratio in the pseudo-cell. So the resource allocation problem is formulated by:

$$\begin{aligned}
(\text{P}_1): \quad & \text{minimize} && \rho_{QoS} \\
& \text{subject to} && 1)\ f_i \in \{1, N_s\} \text{ for all } i, \\
& && 2)\ \sum_{j \in \mathbf{U}^k} n_{ij} \le N_{sc} \text{ for all } k, \text{ if } f_i = 1, \\
& && \quad \sum_{j \in \mathbf{U}^{pc}} n_{ij} \le N_{sc}, \qquad \text{otherwise.}
\end{aligned}$$

The second constraint indicates that the sub-carriers in the SGs with FRF = 1 are reused by N_s cells, whereas the sub-carriers in the SGs with FRF = N_s are divided into N_s cells.

In order to achieve the above goal, we present two algorithms that have different resource allocation architectures. Firstly, as a baseline algorithm for performance comparison, we devise a fully centralized algorithm which determines the resource allocation within the pseudo-cell with full information. For centralized control, we place an ICC that coordinates the cells within the pseudo-cell as depicted in Fig. 4. Each BS sends the information on the rate requirement (Q_j^{req} for all j) and the *instantaneous* channel condition ($\gamma_{ij}(f)$ for all i, j, and f) of all the

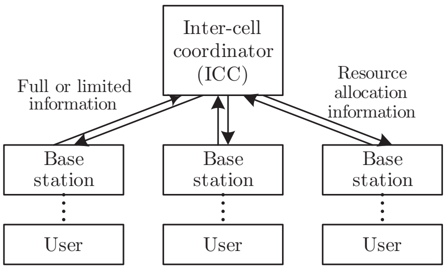

Fig. 4. Resource allocation architecture.

users to the ICC. Based on the received information the ICC performs the resource allocation for all the cells within the pseudo-cell. Noting that the algorithm requires a full-information based coordination, we call it a DRA-FC.

However, in practice, it is difficult, even if not impossible, to obtain the full information about all users reporting to the ICC since even one pseudo-cell consists of multiple sectors belonging to different cells. So we devise a more practical algorithm by employing hierarchical decoupling for the resource allocation between the ICC level and the BS level as follows: At the ICC level, the ICC performs a high-level inter-cell resource allocation with a given limited information. Depending on the information available at the ICC, the following two different algorithms are considered: The first is the case when each BS sends only the *average* channel condition and the rate requirement of each user to the ICC. The second is the case when the information is further reduced to the load of each cell, which is calculated from the average channel condition and the rate requirement of all the users. In either case, the ICC determines the FRF value of all the SGs and distributes the sub-carriers to the constituent cells based on the received information. At the BS level, each BS independently allocates its available sub-carriers assigned by the ICC by using the instantaneous channel conditions of the users. As a limited information is provided to the ICC, we call the algorithm a DRA-LC. In this paper we focus on a stationary network where the average channel conditions of users vary very slowly. As will become clear in Section VI, the DRA-LC algorithm enables us to reduce the signaling overhead significantly.

IV. DYNAMIC RESOURCE ALLOCATION WITH FULL COORDINATION (DRA-FC)

If we have full information about all the users within the pseudo-cell, we may be able to solve the resource allocation problem (P_1) directly. Unfortunately, however, Problem (P_1) is a nonlinear integer programming problem, which is NP-complete [14]. The most widely used method for solving the integer programming problem is the Branch-and-Bound algorithm but it has a worst-case exponential complexity with the exponent determined by the number of integer variables involved [15]. Problem (P_1) has $(|\mathbf{U}^{pc}|+1)N_{sg}$ integer variables, where the sizes of $|\mathbf{U}^{pc}|$ and N_{sg} are both large in general (a few dozens or even hundreds). Therefore, it is unrealistic to determine the optimal solution directly from the formulation of (P_1). So we consider a suboptimal algorithm that can perform near optimal at very low complexity.

In principle, it is most desirable, in view of the QoS violation ratio, if the QoS requirement of each user can be satisfied by consuming a minimum possible number of sub-carriers. This can be realized by allocating sub-carriers in each SG to the users whose channel conditions are the best in the SG. So, for a given SG, we define the *preference index* of each user as the ratio of the user's data rate on the particular SG to the average of the user's data rates on all the SGs. Then, for each SG, we construct a *user preference list* ordered by the preference index for each FRF value: When FRF = 1, the SG is used simultaneously by the N_s cells in the pseudo-cell, so we construct one user list per each cell. When FRF = N_s, each sub-carrier is used by only one cell, so we construct one user list containing all the users in the pseudo-cell. We define the *effective capacity* of each SG as the sum of the maximum number of the users whose rate requirements can be satisfied in each cell, scaled by the percentage of the users belonging to the particular cell among all the users unserved during the previous iteration. The effective capacity yields when the sub-carriers in the SG are allocated to the users according to the user preference list. For each SG, we determine the effective capacity for the both values of FRF and then take the one that yields the larger value. Once the effective capacity values are determined for all SGs, we single out the SG that has the largest value and actually allocate the sub-carriers to those users in the user preference list. Once the sub-carrier allocation is done for the SG with the largest effective capacity as above, we restart constructing the user preference list for all the remaining SGs and for all the remaining users. We repeat the same process until no available sub-carrier remains or all user requirements are satisfied. When two or more users do not get their desired data rate even after completing the above resource allocation process, we conduct a reallocation process as follows: We recall the sub-carriers from the user who has been allocated with the largest number of sub-carriers among the users who did not get the desired data rate. We then reallocate the recalled sub-carriers to the other users. We repeat the reallocation process until the QoS violation ratio cannot be reduced any further.

We detail the DRA-FC algorithm in the following.

A. Construction of User Preference List

Let $R_j^{avg}(f)$ be the average of $R_{ij}(f)$'s over all SGs for an FRF value f, i.e., $R_j^{avg}(f) = 1/N_{sg}\sum_{i=1}^{N_{sg}} R_{ij}(f)$. Then, the preference index of user j for SG i, $p_{ij}(f)$, is given by the ratio of $R_{ij}(f)$ to $R_j^{avg}(f)$. We construct the user preference list arranged in the descending order of $p_{ij}(1)$ in cell k, denoted by $\mathbf{J}_i^k$, and the user preference list ordered by $p_{ij}(N_s)$ in the pseudo-cell, denoted by $\mathbf{J}_i^{pc}$. Let $J_i^k(l)$ and $J_i^{pc}(l)$ denote the l-th element in $\mathbf{J}_i^k$ and $\mathbf{J}_i^{pc}$, respectively.

B. Calculation of the Number of Sub-Carriers

Let $m_{ij}(f)$ be the number of sub-carriers of SG i required to provide the remaining data rate Q_j^{rem} (i.e., the difference between the requirement and the currently allocated data rate) of user j when $f_i = f$. Then, we get the expression $m_{ij}(f) = \lceil Q_j^{rem}/R_{ij}(f)\rceil$, where $\lceil x\rceil$ denotes the smallest integer not smaller than x.

C. Calculation of Effective Capacity and Preferred FRF

For SG i, the effective capacity in cell c when FRF = 1 is given by

$$\psi_i^k(1) = w^k(\bar{j}_i^k + \varepsilon_i^k) \tag{6a}$$

where $\bar{j}_i^k$ is the maximum number of the users whose requirements are satisfied in cell k, i.e., $\bar{j}_i^k = \max\{j|\sum_{l=1}^{j} m_{iJ_i^k(l)}(1) < n_i^k\}$, where n_i^k is the number of the available sub-carriers of SG i in cell k; ε_i^k is the ratio of the number of the remaining sub-carriers to the number of sub-carriers needed to satisfy the full requirement of user $J_i^k(\bar{j}_i^k+1)$, i.e.,

$$\varepsilon_i^k = \frac{n_i^k - \sum_{l=1}^{\bar{j}_i^k} m_{iJ_i^k(l)}(1)}{m_{iJ_i^k(\bar{j}_i^k+1)}(1)}; \tag{6b}$$

w^k is the scaling factor for cell k, defined by $w^k = u^k / \sum_{k=1}^{N_s} u^k$, where u^k denotes the number of the users unserved during the previous iteration (i.e., $Q_j^{rem} > 0$) in cell k. Taking into account different loads among the cell, we scale the capacity by the percentage of the users belonging to the particular cell among the unserved users. Then, the total effective capacity when FRF = 1 in the pseudo-cell is $\psi_i(1) = \sum_{k=1}^{N_s} \psi_i^k(1)$.

The effective capacity when FRF = N_s is determined in a similar manner to be

$$\psi_i(N_s) = \sum_{k=1}^{\bar{j}_i^{pc}} w^{K(J_i^{pc}(k))} + w^{K(J_i^{pc}(\bar{j}_i^{pc}+1))}\varepsilon_i^{pc}, \tag{7a}$$

$$\varepsilon_i^{pc} = \frac{n_i^{pc} - \sum_{l=1}^{\bar{j}_i^{pc}} m_{iJ_i^{pc}(l)}(N_s)}{m_{iJ_i^{pc}(\bar{j}_i^{pc}+1)}(N_s)} \tag{7b}$$

where $\bar{j}_i^{pc}$ denotes the number of the users to be accommodated in the pseudo-cell, i.e., $\bar{j}_i^{pc} = \max\{j|\sum_{l=1}^{j} m_{iJ_i^{pc}(l)}(N_s) < n_i^{pc}\}$; n_i^{pc} the number of the available sub-carriers of SG i in the pseudo-cell; $K(j)$ the index of the cell that user j is associated with.

Once $\psi_i(1)$ and $\psi_i(N_s)$ are both determined, the effective capacity of SG i is given by $\max(\psi_i(1), \psi_i(N_s))$. We call the FRF value that yields the larger effective capacity the *preferred* FRF.

D. Selection of Sub-Carrier Group

After calculating the effective capacities and the candidate FRFs for all SG's, we single out the SG having the largest effective capacity and set the FRF value of the selected SG as the preferred FRF of the SG.

E. Allocation of Sub-Carriers

Once the SG having the largest effective capacity is selected as above, we allocate the sub-carriers of the selected SG to the users according to the user preference list and then update the values of Q_j^{rem}, n_i^k, and n_i^{pc}. Then, we restart the construction of user preference list. We repeat the same process until no available sub-carrier remains or all user requirements are satisfied.

F. Reallocation of Sub-carriers

When two or more users do not get their required data rate even after completing the above resource allocation, we perform a reallocation process as follows: We select the user who has been allocated with the largest number of sub-carriers among the users who did not get the desired data rate. We recall the sub-carriers from this selected user and reallocate the recalled sub-carriers to the other users. We repeat this process until the QoS violation ratio cannot be reduced any further.

V. DYNAMIC RESOURCE ALLOCATION WITH LIMITED COORDINATION (DRA-LC)

Now we introduce the DRA-LC algorithm that can operate with a limited coordination among the neighboring cells while performing close to the DRA-FC algorithm. The DRA-LC algorithm consists of an inter-cell resource allocation and an intra-cell resource allocation. For the inter-cell resource allocation, the ICC distributes the resource to the constituent cells according to their load distribution. We devise two different inter-cell resource allocation algorithms with different signaling information between the BSs and the ICC. In the first algorithm, the ICC gathers the information on the rate requirement and the average channel condition of the users reported by each BS. In the second algorithm, each BS first calculates the load of its cell and then reports it to the ICC. In either case, based on the received information from the BSs, the ICC determines the number of SGs with FRF = 1 and that with FRF = N_s and then divides the sub-carriers in the SGs with FRF = N_s into the N_s cells. For the intra-cell resource allocation, each BS allocates the sub-carriers assigned to it to the users based on their instantaneous channel conditions available at the BS.

We detail the DRA-LC algorithm in the following.

A. Inter-Cell Resource Allocation Algorithm 1

In the first inter-cell resource allocation algorithm, the ICC determines the inter-cell resource allocation based on the information received from the BSs. We first determine the preferred FRF value of each user as follows: Let $m_j^{avg}(f)$ denote the expected number of sub-carriers required for supporting the rate requirement of user j when FRF = f, which is given by $m_j^{avg}(f) = Q_j^{req}/R_j^{avg}(f)$ and x_j the indicator denoting if user j prefers the FRF value of 1 (x_j is 1 if the preferred FRF of user j is 1 and 0 otherwise). We determine the preferred FRF values of the users such that the total number of sub-carriers required to meet the rate requirement of all the users be minimized. Specifically, the inter-cell coordinator solves the following problem to determine x_j's, for the given Q_j^{req}'s and $R_j^{avg}(f)$'s, $f = 1, N_s$.

$$\begin{aligned}
(\mathrm{P}_2): \quad & \text{minimize} \quad z + \sum_{j\in\mathbf{U}^{pc}} (1-x_j) m_j^{avg}(N_s) \\
& \text{subject to} \quad \sum_{j\in\mathbf{U}^k} x_j m_j^{avg}(1) \le z \text{ for all } k, \\
& \qquad\qquad\quad z \ge 0,\ x_j \in \{1, 0\}
\end{aligned}$$

where z is an auxiliary variable indicating the required number of sub-carriers with FRF = 1.

Problem (P_2) is a linear integer programming problem. Instead of solving it directly, we find a near-optimal solution as follows: By relaxing the integer control variables into real variables, we first determine the unique optimal real-number solution x_j^*'s. Then, we search a near-optimal integer solution that is the nearest to this real-number solution.

Then, we determine the number of SGs with FRF = 1, that with FRF $= N_s$, and the number of sub-carriers allocated to cell k in each SG with FRF = N_s, $N_{H(k)}$, for $k = 1, 2, \cdots, N_s$. Assuming that the sub-carriers are allocated to the users according to the preferred FRF, the required numbers of sub-carriers with FRF = 1 and FRF = N_s to meet the user j's requirement are given by $x_j m_j^{avg}(1)$ and $(1 - x_j)m_j^{avg}(N_s)$, respectively. We determine N_L and $N_{H(k)}$'s such that the effective capacity, defined in Section III, is maximized when serving the users in an ascending order of the required number of sub-carriers. As we have only the knowledge of the average channel condition, we determine only the number of SGs with different FRF and then randomly select the SGs with each FRF.

B. Inter-Cell Resource Allocation Algorithm 2

In the second inter-cell resource allocation algorithm, each BS first calculates the load of its cell as follows: Differently from the first algorithm, we determine the preferred FRF value of each user based on the ratio $r_j \equiv R_j^{avg}(N_s)/R_j^{avg}(1)$. If r_j is larger than N_s, meaning that the interference avoidance gain is large, then N_s is taken as the preferred FRF value of user j. Otherwise, 1 is the preferred value. Note that we set the threshold to N_s since if one sub-carrier in the SG with FRF = N_s is allocated to a user then it cannot be used by any user in the other $N_s - 1$ cells, thus effectively N_s sub-carriers are allocated to the user. Based on such preferred FRF values, users are divided into two groups. Let $\mathbf{U}_{FRF}^k(1)$ and $\mathbf{U}_{FRF}^k(N_s)$ be the index sets of the users who prefer the FRF values 1 and N_s, respectively, in cell k. Then, we define the *load* for the FRF value of f (=1 or N_s) in cell k to be

$$\lambda^k(f) \equiv \sum_{j \in \mathbf{U}_{FRF}^k(f)} m_j^{avg}(f). \tag{8}$$

Each BS sends the above load information to the ICC. Then, since the loads for FRF = 1 may be uneven among the different cells, we perform the additional procedure to balance the loads. The ICC sends the average value λ^{avg} ($\equiv 1/N_s \sum_{k=1}^{N_s} \lambda^k(1)$) and then the BS recalculate its load as follows: We rearrange the index sets $\mathbf{U}_{FRF}^k(1)$ and $\mathbf{U}_{FRF}^k(N_s)$ of each cell whose load $\lambda^k(1)$ is larger than λ^{avg} in such a way that the users having the highest value of r_j in $\mathbf{U}_{FRF}^k(1)$ be transferred to $\mathbf{U}_{FRF}^k(N_s)$, thereby minimizing the loss caused by allocating a non-preferred FRF. If we denote by $\mathbf{J}_{FRF}^k(f)$ the index list of users arranged in the descending order of r_j in $\mathbf{U}_{FRF}^k(f)$ and by $J_{FRF}^k(f,l)$ the l-th element in $\mathbf{J}_{FRF}^k(f)$, then the load for FRF = 1 changes to $\hat{\lambda}^k(1) = \sum_{l=\underline{j}^k(1)+1}^{|\mathbf{U}_{FRF}^k(1)|} m_{J_{FRF}^k(1,l)}^{avg}$ where $\underline{j}^k(1)$ denotes the number of the transferred users, i.e, $\underline{j}^k(1) = \arg\min_j \left| \sum_{l=j+1}^{\mathbf{U}_{FRF}^k(f)} m_{J_{FRF}^k(1,l)}^{avg} - \lambda^{avg} \right|$. In contrast, the load for FRF = N_s increases to $\hat{\lambda}^k(N_s) = \sum_{l=1}^{\underline{j}^k(1)} m_{J_{FRF}^k(1,l)}^{avg} + \sum_{l \in \mathbf{U}_{FRF}^k(N_s)} m_l^{avg}$. Conversely, for each cell whose $\lambda^k(1)$ is smaller than λ^{avg}, we increase $\lambda^k(1)$ by transferring some users from $\mathbf{U}_{FRF}^k(N_s)$ to yield $\hat{\lambda}^k(1) = \sum_{j \in \mathbf{U}_{FRF}^k(1)} m_j^{avg} + \sum_{l=\underline{j}^k(N_s)+1}^{|\mathbf{U}_{FRF}^k(N_s)|} m_{J_{FRF}^k(N_s,l)}^{avg}$, where $\underline{j}^k(N_s) = \arg\min_j \left| \sum_{l \in \mathbf{U}_{FRF}^k(1)} m_l^{avg} + \sum_{l=j+1}^{|\mathbf{U}_{FRF}^k(N_s)|} m_{J_{FRF}^k(N_s,l)}^{avg} - \lambda^{avg} \right|$ and $\hat{\lambda}^k(N_s) = \sum_{l=1}^{\underline{j}^k(N_s)} m_{J_{FRF}^k(N_s,l)}^{avg}$.

Then, we determine N_L, the number of SGs with FRF = 1, according to the ratio of the total load for FRF = 1 to that for FRF = N_s in the pseudo-cell as follows:

$$N_L = \left\langle N_{sg} \left(\frac{1/N_s \sum_{k=1}^{N_s} \hat{\lambda}^k(1)}{1/N_s \sum_{k=1}^{N_s} \hat{\lambda}^k(1) + \sum_{k=1}^{N_s} \hat{\lambda}^k(N_s)} \right) \right\rangle \tag{9}$$

where $\langle \cdot \rangle$ denotes the rounding-off operation. Note that the total load for FRF = 1 is defined to be the average value of $\hat{\lambda}^k(1)$'s over the N_s cells since the SGs with FRF = 1 are reused by them, whereas the total load for FRF = N_s is defined as the sum of $\hat{\lambda}^k(N_s)$'s. Finally we select N_H ($\equiv N_{sg} - N_L$) SGs with FRF = N_s randomly among all SGs and divide the sub-carriers in the N_H SGs in proportion to the values of $\hat{\lambda}^k(N_s)$'s among the N_s cells.

C. Intra-Cell Resource Allocation Algorithm

Since the intra-cell resource allocation is a single-cell problem, we can devise a simple algorithm to minimize the QoS violation ratio in each cell as follows: We first determine the best possible SG of each user based on the effective data rate as follows: We define the *effective data rate*, R_{ij}^{eff}, as the data rate normalized by the number of sub-carriers allocated effectively to user j in SG i, i.e.,

$$R_{ij}^{eff} = \begin{cases} R_{ij}(N_s)/N_s, & \text{if } f_i = N_s, \\ R_{ij}(1), & \text{otherwise.} \end{cases} \tag{10}$$

Then, the best SG of user j is the SG that yields the highest value of R_{ij}^{eff} among the remaining SGs. Therefore, for intra-sector resource allocation, we first select the user who has the largest ratio of the remaining data rate Q_j^{rem} to the required data rate Q_j^{req} and then allocate to the selected user a sub-carrier in its best SG. We repeat this process until no available sub-carrier remains or all user requirements are satisfied. In case two or more users do not get their required data rate even after completing the above resource allocation, we perform the same reallocation process as the DRA-FC algorithm.

VI. NUMERICAL RESULTS

We consider a network composed of 19 cells of hexagonal 3-sectorized cell structure and conduct various computer simulations. We set the values of the involved parameters as follows: carrier frequency is 2 GHz; bandwidth, B, 10 MHz; the number of sub-carriers, 1024; the number of SGs, N_{sg}, 64; the number of data sub-carriers per SG, N_{sc}, 15; cell radius, 1km; and the target BER, 10^{-5}.

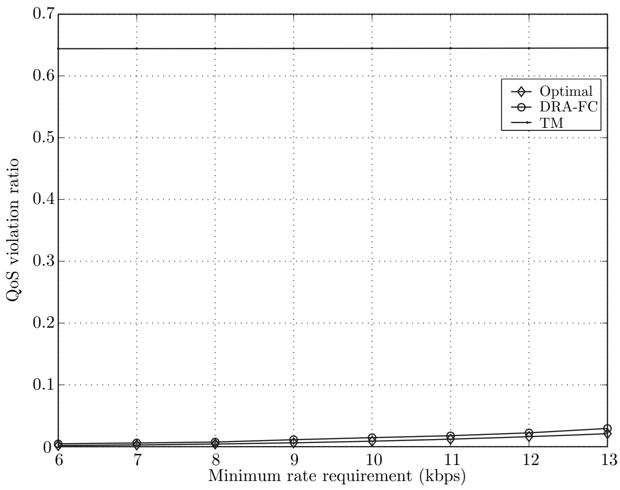

Fig. 5. Performance comparison of the DRA-FC algorithm, the optimal solution, and the throughput maximization (TM) algorithm.

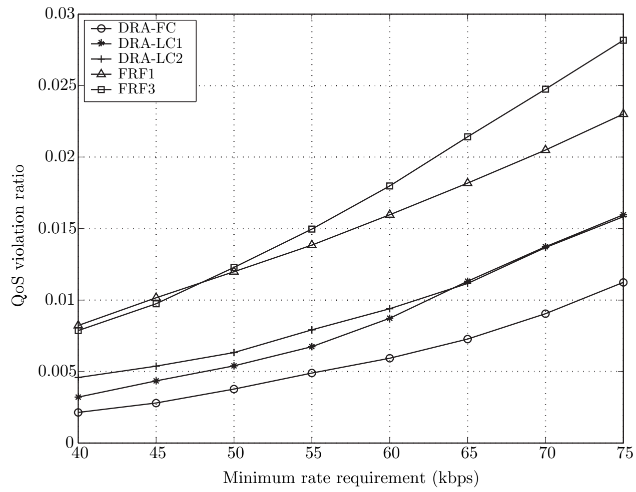

Fig. 6. QoS violation ratios of various algorithms with respect to the minimum rate requirement.

We model the channel gain $g(t)$ at time t in the form [16]

$$10\log_{10} g(t) = -28.6(\text{dB}) - 10\kappa \log_{10} d + u + 10\log_{10} j(t) \tag{11}$$

where κ is the path loss exponent, which we set to 3.5; d (in meters) the distance between the user and the BS; u the shadow fading loss modeled by a zero-mean Gaussian random variable with the standard deviation $\sigma_s = 8$ dB; and $j(t)$ the multipath fading process represented by the Jakes' model [17].

We conduct simulations on DRA-FC, -LC1, -LC2, fixed FRF 1, fixed FRF 3, and, occasionally, on the *throughput maximization* (TM) algorithm as well. In the fixed FRF 1 algorithm all cells reuse all the sub-carriers, while in the fixed FRF 3 algorithm 1/3 sub-carries are assigned to each cell. The TM algorithm is designed to maximize the total throughput by determining the FRF value and allocating sub-carriers to the users in such a way that data transmission is done at the highest rate on each sub-carrier.

A. Performance of DRA-FC Algorithm

Prior to starting the main simulations, we evaluate the performance of the DRA-FC algorithm in comparison with the optimal results directly obtained by solving Problem (P1). In this particular simulation, we only consider the case of 3 SGs and a small number of users, as the computational time required for solving the nonlinear integer programming is extremely long. Specifically, we randomly located 15 users over each pseudo-cell and increase the requested minimum data rate from 6 kbps to 13 kbps. Fig. 5 depicts the resulting QoS violation ratio of the DRA-FC in comparison with the optimal results. We observe that the DRA-FC algorithm can achieve a performance level that is close to the optimal solution. In addition, we observe that the TM algorithm yields a very high QoS violation ratio. The QoS violation is very likely to occur for the users located at the cell boundary. Therefore, the dynamic resource allocation for QoS violation minimization can improve the performance of the cell-boundary users significantly by exploiting the interference avoidance gain.

B. Comparison Among DRA-FC, -NC, and Fixed-FRF Algorithms

We compared the DRA-LC algorithm with the DRA-FC and fixed FRF algorithms. We randomly located 45 users over each pseudo-cell. Fig. 6 depicts the resulting QoS violation ratio of the various algorithms with respect to the minimum rate requirement. We observe that the DRA-LC and the DRA-FC algorithms outperforms the fixed-FRF algorithms. This shows the benefit of the dynamic controlling of the FRF value of each sub-carrier. We also observe there is little difference between the DRA-LC1 and -LC2 algorithms. This indicates that the load defined in the DRA-LC2 algorithm can well represent the average channel conditions and the rate requirement of all the users with small loss of performance. Further, we observe that the DRA-LC1 and -LC2 algorithms significantly reduces the gap between the DRA-FC algorithm and the fixed FRF algorithms. This indicates that the DRA-LC2 algorithm can obtain high interference avoidance gain by utilizing only the load information for the inter-cell resource allocation while exploiting the fast channel dynamics only at the BS level.

Then, we conducted similar simulations under non-uniform load scenario with the degree of non-uniformity changing as follows: Assuming that the total number of users in one pseudo-cell is fixed at 48, we increase the number of users in cell 1 from 24 to 36, while keeping the other users evenly distributed in cells 2 and 3. We set the minimum rate requirement to $Q_j = 60$ kbps for all the users. Fig. 7 depicts the resulting QoS violation ratios with respect to the number of users in cell 1. The fixed-FRF algorithm yields a high QoS violation ratio when many users concentrate on cell 1 due to the frequent QoS violation in the heavily loaded cell (i.e., cell 1). So there occurs a large unbalance among the performances of the users in different cells. However, in the case of DRA-FC and -LC algorithms, the QoS violation ratio is kept low in spite of non-uniform load distribution. This shows that the load-adaptive inter-cell resource allocation improves the performance of the users in the heavily loaded cell, thus achieves better fairness among the users belonging to different cells.

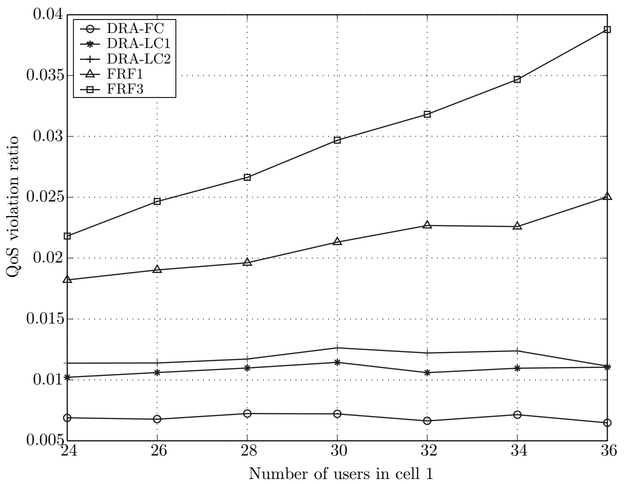

Fig. 7. QoS violation ratios for various algorithms under non-uniform load distribution.

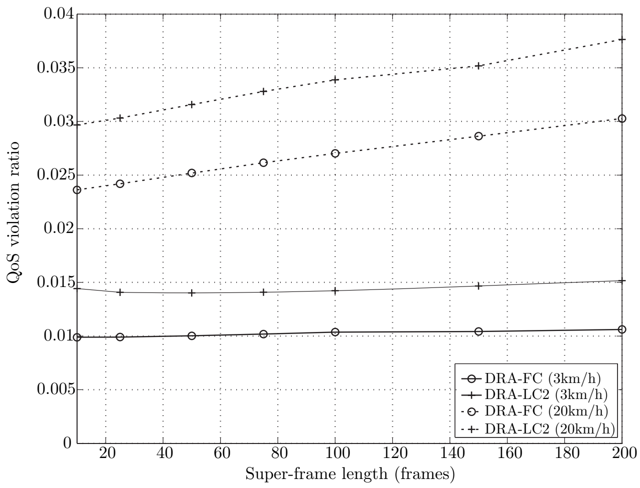

Fig. 8. QoS violation ratios of the DRA-FC and DRA-LC2 algorithms with respect to the super-frame length under two mobile velocities, 3 and 20 km/h.

C. Performance in Non-Stationary Network

As mentioned earlier, the DRA-LC algorithm is targeted for a stationary network where the average channel conditions of users changes very slowly. In the stationary network, we can use a large update period for the inter-cell resource allocation based on the average channel condition, thus resulting in a very small signaling overhead. However, in the case of non-stationary networks, the update period should be reduced as the mobility of the users increases. In order to investigate the impact of the mobility, we consider a frame and super-frame structure in the time domain, with each super-frame composed of multiple frames. We assume that the channel condition of each user is fixed during each frame but varies frame to frame. We model the shadow fading loss as a Gaussian process filtered by a first-order low-pass filter [18], which takes the form

$$u_{t+1} = \epsilon u_t + \sqrt{1-\epsilon} v_t \tag{12}$$

where t is the frame index; v_t a zero-mean Gaussian random variable with variance σ_s^2; and ϵ a parameter that controls the spatial correlation of the shadowing given by

$$\epsilon = \epsilon_D^{vT_f/D} \tag{13}$$

where ϵ_D is the correlation between two points separated by a spatial distance of D; v the velocity of the user; and T_f the frame duration. We take the values $D = 10$ m and $T_f = 2$ ms. Under this model, we perform the intra-cell resource allocation frame based and the inter-cell resource allocation super-frame based for the case of the DRA-LC algorithms.

We examined the impact of the super-frame length on the performance of the DRA-LC algorithms for two mobile velocities, 3 and 20 km/h. We randomly located 45 users over each pseudo-cell and set the minimum rate requirement $Q_j = 60$ kbps. Fig. 8 depicts the resulting QoS violation ratio of the DRA-FC and the DRA-LC2 algorithms with respect to the super-frame length. We observe that in the case of low velocity (i.e., 3 km/h), the QoS violation ratio almost does not change as the super-frame length increases. This implies that the super-frame length may be increased up to hundreds of ms in nomadic environment. On the other hand, the case of high velocity (i.e., 20 km/h) yields a lager QoS violation ratio, with the difference between the two cases increasing as the super-frame size increases. It happens because the gap between the outdated feedback information and the real channel condition increases when super-frame length is large as compared with the speed of the channel variation. This indicates that we need frequent inter-cell signaling in fast-varying channel environment, consequently inducing high signaling overhead.

VII. CONCLUDING REMARKS

In this paper, we have introduced the DRA algorithms that can minimize the QoS violation ratio while satisfying the requested minimum data rate. It was considered for the OFDMA system that is capable of dynamically controlling the FRF value of each sub-carrier. For this system, we have devised the load-adaptive resource allocation algorithms that determine the FRF values of the sub-carriers and allocate the sub-carriers to the users according to their sensitivity to the inter-cell interference and the load distribution. It turned out through numerical results that the proposed algorithms significantly reduce the QoS violation ratio especially for the cell-boundary users and improve the fairness among the neighboring cells with different loads, when compared with the throughput maximization and the fixed FRF algorithms.

We have investigated how to design the resource allocation architecture for low signaling overhead. As a reference for comparison we have devised a heuristic algorithm, DRA-FC, that can perform close to the optimal solution at a lower computational complexity. However, the DRA-FC algorithm cannot be used in practice as it requires a high signaling overhead caused by the full-information based coordination among the neighboring cells. As a practical algorithm, we introduced the DRA-LC algorithms that can solve the resource allocation problem hierarchically, at low signaling overhead, by decoupling the resource allocation into the ICC and the BS levels. We have devised two different versions which differ in the signaling information delivered from the BS to the ICC: In the DRA-LC1 algorithm, we limited the information to the pairs of the average channel condition and the rate requirement of the users, whereas in the DRA-LC2 algorithm, we further reduced the signaling information by adopting the concept of load which incorporates the average channel condition and the rate requirement of all the users in one parameter. In either case, the ICC performs the load-adaptive inter-cell resource allocation with the given limited information, and the BS performs the intra-cell resource allocation with the full information about its own cell. We have demonstrated through simulation results that the inter-cell signaling may be arranged to take place infrequently in stationary networks as well as non-stationary nomadic networks. In particular, the DRA-LC2 algorithm turned out to improve the performance significantly near to the DRA-FC algorithm even at the very limited signaling overhead. We may conclude that with such enhanced features in both performance and overhead, the DRA-LC2 algorithm should prove very useful for practical applications.

It is worth noting that the distinguished performance of the DRA-LC2 algorithm is made possible due to the following two features which are both very demanding in multi-cell environments: First, the DRA-LC2 algorithm mitigates the performance deterioration by inter-cell interference especially for the users who are located at the cell boundary. Secondly, the DRA-LC2 algorithm provides an improved fairness among the users in different neighboring cells under non-uniform load distribution. The former results from the interference avoidance gain obtained by effectively controlling the FRF of the sub-carriers, and the latter from the load balancing gain obtained by adopting the load-adaptive inter-cell resource allocation.

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