Channel allocation in multi-cell OFDMA downlink systems

(Invited Paper)

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Abstract— As wireless networks evolve to orthogonal frequency division multiple access (OFDMA) systems, inter-cell interference control becomes a critical issue in radio resource management. The allocation of the same channels in neighbor cells cause inter-cell interference, so the channel allocation needs to be taken carefully to lower the inter-cell interference. For channel allocation, we consider two types of approach: centralized and distributed. In centralized approach, there exists a central server for channel allocation. This approach gives optimal allocation results, but requires a lot of information exchanges and calculations. In this paper, under the assumption of static users, we tackle a channel allocation problem by using the centralized approach and propose heuristic algorithms that require low complexity. Our proposed algorithms show good performance in terms of throughput and power consumption compared to the other centralized schemes. Our algorithms of power allocation with fixed increase (PAFI) and rate allocation with fixed increase (RAFI) show 2 to 3% lower throughput compared to the optimal scheme while they reduce the power consumption by up to 40%. Our schemes show approximately 10% more throughput and 70% less power consumption compared to the scheme of frequency reuse factor 1 that is fully distributed. In distributed approach, each cell independently tries to allocate channels to lower the interference level without using a centralized server. We sketch a way of dynamic channel allocation considering the interference range for our distributed approach.

I. INTRODUCTION

As wireless networks evolve, some standards to support packet data services of high bandwidth have been developed. IEEE 802.16e [1], 802.20, and 3GPP long term evolution (LTE) are the recently developed standards regarded as the preliminary versions for next generation wireless communications. The common feature of these standards is in use of orthogonal frequency division multiple access (OFDMA) instead of code division multiple access (CDMA) for multiple access. OFDMA systems achieve higher cell throughput than CDMA systems by applying the different adaptive modulation control (AMC) scheme for each channel [2]. In OFDMA systems, data is transmitted over many mutually orthogonal sub-carriers, so multiple data streams can be transmitted over different sub-carriers. In real systems, resource allocation in frequency axis is performed in the unit of sub-channel that possibly uses multiple sub-carriers. OFDMA systems allocate different sub-channels for different mobile terminals (MTs) to achieve good performance by taking advantage of highly selective frequency environments.

In downlink OFDMA systems, allocation of multiple channels is a main part of radio resource management. The allocation messages are broadcasted at the beginning of each frame. The first step in resource allocation is searching for available sub-channels that are not allocated yet. If the inter-cell interference control forbids the use of some sub-channels, those will be excluded from allocation. In channel allocation, the base station (BS) considers each MT’s quality of service (QoS), fairness, and channel feedback information. The transmit power can be also adjusted if the power control is possible. Since the power allocation in a single cell does not show many advantages considering its implementation complexity, the fixed transmit power is usually used.

There are two types of approaches to handle the inter-cell interference problem: centralized and distributed. In centralized approach, a central controller collects all channel information from all cells and performs channel allocation. In this approach, static schemes determine an available channel set for each cell without using any dynamic information while adaptive schemes dynamically allocate channels considering each MT’s requirements and current channel information. The static schemes design the frequency reuse factor (FRF) at the cell planning stage [3]. For example, FRF $N$ divides the given frequency band equally for $N$ neighboring cells, while FRF 1 allows each cell to use the whole bandwidth. So the cell throughput in FRF 1 is larger compared to that in FRF 3 or 7 scheme. However FRF 1 scheme can not support cell boundary MTs properly because of strong inter-cell interference [4]. In [5], the concept of adaptive frequency reuse was introduced, and two centralized approaches were proposed. They have the objective of maximizing the spatial reuse without assuming a specific architecture. In [6], the concept of fractional frequency reuse and the management algorithm for the reuse set were proposed. The algorithm defines non-integer reuse factor and updates the reuse set dynamically.

In this paper, we investigate the channel allocation problem in a multi-cell environment, and consider centralized and distributed allocation algorithms assuming no mobility. For centralized method, a central controller has the information about all involved cells. In this case, we can formulate the system design for obtaining the maximum total throughput as an optimization problem. However the complexity is not tractable, so we consider some heuristic algorithms that increase transmit
power in a cell only when the total throughput increases, while fixing either the amount of power or rate increase. They show good throughput performance with reduced complexity and power consumption compared to FRF 1 scheme.

For distributed method, we propose dynamic channel allocation that uses the interference range. With interference range, we can estimate how much inter-cell interference is generated and which is the main source of the interference.

In Section II, we formulate the optimization problem for centralized channel allocation in OFDMA multi-cell environments, and consider two heuristic algorithms to solve it practically. Numerical analysis and simulation results are given in Section III. In Section IV, we consider channel state estimation and explain distributed channel allocation algorithms using the interference range. We conclude our paper in Section V.

II. CENTRALIZED CHANNEL ALLOCATION SCHEMES

In OFDMA systems, channel allocation is a primary component for radio resource management in BS. In a single cell system, the channel allocation is a trivial issue because the BS can allocate any available channels to each MT. In multi-cell systems, however, the channel allocation needs to be careful. The use of the same channel at some neighboring cell causes the inter-cell interference that lowers the system throughput. Thus the channel allocation in multi-cell systems needs coordination among cells. There are two types of channel allocation method: centralized and distributed. In this section, we formulate the channel allocation problem in multi-cell downlink OFDMA system that aims at maximizing the total throughput.

A. System model

Fig. 1 shows an example of multi-cell system and a channel allocation controller. In each cell, the BS periodically sends each MT’s information to the controller, and the controller sends a channel allocation result message to each BS. The message exchange is performed through wired-line. Our considered system does not allocate channels dynamically, so each BS uses the same channel during the channel allocation period. The message sent to the controller by each BS contains channel status information for each MT and all the channel allocation requests. Then the controller performs channel allocation to each MT and power allocation to each channel.

B. Optimal channel allocation

For formulation, we consider the channel allocation for an MT in cell $i$. Assume that an MT needs one channel. So an MT in each cell which considers to use the same channel is of our interest $^1$. Assuming there are $N$ cells, we define the following for each channel.

- $P_i$: transmit power for the considered channel in cell $i$
- $g_{ij}$: channel gain between the BS in cell $j$ and the MT in cell $i$, $1 \leq i, j \leq N$
- $R(SINR)$: rate function

$^1$So, we omit the channel index in defining variables.

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- $a_j$: channel allocation indicator; if $j$-th cell allocates the considered channel, $a_j = 1$, and otherwise, 0
- $A$: channel allocation vector; $A = (a_1, \cdots, a_N)$

Assuming that each channel gain is known and the data rate $R$ is determined by SINR, we can express the interference experienced by the considered MT as

$$I_i = \sum_{j=1, j \neq i}^{N} P_0 g_{ij} a_j, \quad (1)$$

and the SINR as

$$SINR_i = \frac{P_0 g_{ii}}{I_i + N_i} = \frac{P_0 g_{ii}}{P_0 \sum_{j=1, j \neq i}^{N} g_{ij} + N_i} \quad (2)$$

where $N_i$ is the noise power at cell $i$. As the total cell throughput is given by $T(A) = \sum_{i=1}^{N} R(SINR_i)$, we can express the optimization problem as

$$\max_A T(A). \quad (3)$$

By integer programming we can obtain the solution that has the form of channel allocation vector. Exhaustive searching is a common approach to solve this and requires the complexity of $O(2^N)$. Therefore we propose a method that solves this problem in polynomial time by using relaxation and some heuristics. Relaxing the integer constraint of $a_i$ to a real number in $[0, 1]$ makes the problem become an optimal power control problem, which can be solved by the feasible direction method [13]. For a given initial channel allocation $A^0$, we can express the allocation vector at step $k$ as

$$A^{k+1} = A^k + \delta \nabla T(A^k) \quad (4)$$

where $\nabla T(A)$ is the gradient of $T(A)$ and $\delta$ is a constant positive stepsize.
For instance, if $M$-ary quadrature amplitude modulation (M-QAM) [14] is used, the rate is given by $R(SINR) = C_1 \cdot \ln(1 + C_2 \cdot SINR)$ where $C_1$ and $C_2$ are the system dependent parameters. The $i$th component of $\nabla T(A)$ is given by

$$
\frac{\partial T(A)}{\partial a_i} = \frac{C_1 C_2 \cdot SINR_i}{1 + C_2 \cdot SINR_i a_i} - \sum_{j=1,j \neq i}^{N} \frac{C_1 C_2 SINR_j}{1 + C_2 SINR_j} \frac{g_{ij}P_0}{\sum_{l=i,l \neq j}^{N} g_{il}a_l + N_i}.
$$

(5)

Then we can express $a_i$ at step $k$ as

$$
a_i^k = \begin{cases} 
0 & \text{if } a_i^k + \delta \frac{\partial T(A)}{\partial a_i} \leq 0, \\
1 & \text{if } a_i^k + \delta \frac{\partial T(A)}{\partial a_i} \geq 1, \\
\text{otherwise}
\end{cases}
$$

(6)

As the problem is not convex, the solution can be suboptimal depending on the given initial allocation vector.

C. Heuristic algorithms

The relaxation from integer to real number makes the resource management more complex because power allocation for an MT affects all other transmissions. Here we design a practical algorithm that achieves acceptable performance with low complexity.

Our approach uses a greedy algorithm that increases power by $P_0\Delta a_i$ as long as the total throughput increases. For step $k$, we express the allocation vector as $A^k = (a^k_1, \ldots, a^k_N)$. If cell $i$ is allocated for more power of $P_0\Delta a_i$, the allocation vector becomes $A^k_i = (a^k_1, \ldots, a^k_i + \Delta a, \ldots, a^k_N)$. Then we can write the algorithm for power allocation with fixed increase (RAFI) as the following.

1. Initialize for all MTs $a_i^0 \leftarrow 0$, $Q \leftarrow \{1, \ldots, N\}$, and $k \leftarrow 0$

2. Find $i$

   $i \leftarrow \arg \max_{j \in Q} T(A_j^k)$

   If $T(A_i^k) \leq T(A_k^k)$, end.

3. Update

   $a_i^k \leftarrow a_i^k + \Delta a$

   If $a_i^k \geq 1$, $Q \leftarrow Q \cup \{i\}$

   If $Q = \phi$, end.

   $a_j^{k+1} \leftarrow a_j^k$ for all $j \neq i$

   $k \leftarrow k + 1$ and go to (2).

In phase (2), the algorithm calculates the total throughput according to the increased power allocation and selects cell that shows the highest throughput increment. If the tried power increment does not show throughput increase any longer, the algorithm ends. In phase (3), the algorithm updates the parameters. Cell selection directly means MT selection because only one MT in each cell considers to use the same channel. Only the selected MT is allocated more power while the others are at the same power. At each iteration, RAFI requires the calculation complexity of $O(N)$.

Similarly, we can design an algorithm by fixing the rate increment $\Delta r$. For fixed $\Delta r$, power increment varies according to each MT’s channel condition. As the SINR increment is given by $\Delta SINR_i = S(\Delta a_i) = \frac{P_0\Delta a_i}{\sum_{j=1,j \neq i}^{N} g_{ij}a_j + N_i}$ and power increment by the inverse function of $S(\Delta a_i)$, we can write the algorithm for rate allocation with fixed increase (RAFI) as follows.

1. Initialize for all MTs $a_i^0 \leftarrow 0$, $r_i^0 \leftarrow 0$, $Q \leftarrow \phi$, and $k \leftarrow 0$

2. Calculate the SINR and rate for each MT

3. Calculate $\Delta a_i^k$ for all $i$

   $\Delta SINR_i^k \leftarrow R^{-1}(r_i^k + \Delta r) - SINR_i^k$

   $\Delta a_i^k \leftarrow S^{-1}(\Delta SINR_i^k)$

   If $T(A_i^k) > T(A_k^k)$ and $a_i^k + \Delta a_i^k \leq 1$, $Q \leftarrow Q \cup \{i\}$

   If $Q = \phi$, end.

4. Find $i$

   $i \leftarrow \arg \min_{j \in Q} T(A_j^k)$

5. Update

   $a_i^{k+1} \leftarrow a_i^k + \Delta a_i^k$

   $a_j^{k+1} \leftarrow a_j^k$ for all $j \neq i$

   $Q \leftarrow \phi$ and $k \leftarrow k + 1$

   Go to (2).

RAFI calculates the total throughput according to the allocated power in phase (3) and selects the MT that shows the highest throughput increment in phase (4). At each iteration, RAFI has the complexity of $O(N)$.

III. NUMERICAL RESULTS

To examine our proposed algorithms, we perform simulations assuming that the channel gain is determined by path loss only, and all channel gains are known for MTs and BSs. In simulations, we compare the relaxed optimal channel allocation scheme with FRF 1 and 3 schemes first, and with our heuristic algorithms.

Simulations are performed for a simple topology of non-sectored 19 cells with the cell radius 1000m each. 21 users per cell are randomly distributed. We executed simulations
A. Channel state estimation

In optimal channel allocation, the controller should know all the channel states between MTs and BSes. The state information include not only the state between an MT and the serving BS but also the state between the MT and its neighbor BSes, which are expressed as $g_{ii}$ and $g_{ij}$ in eq. (2), respectively. In real systems, it is not possible to estimate the channel state between an MT and its neighbor BSes exactly, so the optimal channel allocation is not implementable. Here we introduce a method for approximate channel state estimation.

Our proposed method uses a pre-calculated channel gain table according to cell area partitioning. The area of cell $i$ is divided to $L$ partitions that are expressed as $P_l$ where $1 \leq l \leq L$. Let’s define $S_i$ as the set of neighbor BSes interfering with an MT of cell $i$. If the MT in cell $i$ is located in partition $P_l$, the channel gain $g_{ij}, j \in S_i$, can be approximated to a fixed value and we denote it by $\tilde{g}_{ijl}$. If the neighbor BS $j$ is located at $x_j$, $\tilde{g}_{ijl}$ can be expressed as

$$\tilde{g}_{ijl} = \frac{1}{A_l} \int_{P_l} g_{ij}(x, x_j) \, dx,$$

where $A_l$ is the area of partition $P_l$. The approximated channel gain can be kept in a lookup table. By using the table, the channel gain between an MT in cell $i$ and neighbor BSes can be estimated according to the partition where the MT is located.

In our proposed method, the partitioning method is important. With the number of partitions, the approximated value approaches the real channel gain, but the estimation of MT’s location becomes difficult and the table size of pre-calculated $\tilde{g}_{ijl}$ becomes larger. Fig. 3 shows an example of cell partitioning. Cell area is divided into cell center and cell boundary, and each of which is divided into 3 partitions. If an MT is located in the cell center area, it is not interfered with by neighbor BSes much. The performance analysis of the channel gain approximation using the partitioning needs further study.

B. Distributed channel allocation using the interference range

The main drawback of centralized approach is the overhead of control information exchange between a central controller and each BS. In this subsection, we consider distributed channel allocation where each BS allocates channels independently.

In distributed approach, the BS allocates a channel for each MT whenever requested and also considers power allocation.

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### TABLE I

<table>
<thead>
<tr>
<th>Level</th>
<th>Modulation</th>
<th>Coding rate</th>
<th>Required SIR</th>
<th>Data rate (kbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>QPSK</td>
<td>1/12</td>
<td>-1.8</td>
<td>9.78</td>
</tr>
<tr>
<td>2</td>
<td>QPSK</td>
<td>1/6</td>
<td>-0.3</td>
<td>19.55</td>
</tr>
<tr>
<td>3</td>
<td>QPSK</td>
<td>1/3</td>
<td>2.6</td>
<td>39.11</td>
</tr>
<tr>
<td>4</td>
<td>QPSK</td>
<td>2/5</td>
<td>4.2</td>
<td>46.93</td>
</tr>
<tr>
<td>5</td>
<td>16QAM</td>
<td>1/4</td>
<td>5.2</td>
<td>58.67</td>
</tr>
<tr>
<td>6</td>
<td>16QAM</td>
<td>1/3</td>
<td>6.8</td>
<td>78.21</td>
</tr>
<tr>
<td>7</td>
<td>16QAM</td>
<td>2/5</td>
<td>8.3</td>
<td>93.87</td>
</tr>
<tr>
<td>8</td>
<td>16QAM</td>
<td>1/2</td>
<td>11.3</td>
<td>117.33</td>
</tr>
</tbody>
</table>

### TABLE II

<table>
<thead>
<tr>
<th>Throughput (kbps)</th>
<th>Optimal scheme</th>
<th>FRF 1 scheme</th>
<th>PAFI</th>
<th>RAFA</th>
<th>Delta $a$</th>
<th>Delta $r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>779.3</td>
<td>768.2</td>
<td>750.4</td>
<td>747.5</td>
<td>763.8</td>
<td>753.9</td>
<td></td>
</tr>
<tr>
<td>Power (mW)</td>
<td>7.17</td>
<td>20.0</td>
<td>3.83</td>
<td>6.78</td>
<td>4.35</td>
<td>3.82</td>
</tr>
</tbody>
</table>

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**Fig. 3.** Example of cell partitioning.
In [7], a distributed non-cooperative game approach was used to allocate channels with minimum power consumption. The dynamic channel allocation schemes in [9], [10], are coupled with scheduling that uses the information about channel condition. In this schemes, scheduling considers the inter-cell interference as well as MT’s QoS requirements. However it is hard to model the channel condition considering the inter-cell interference because of its dependency on neighbor cells’ channel allocations. Thus, if the main purpose of scheduling is not in controlling the inter-cell interference, it can be simply assumed that channel allocations in neighbor cells are fixed and the channel condition is modeled as a random process like Gaussian [11].

Our distributed method considers the interference range in channel allocation that was originally used for spatial reuse in ad hoc and sensor networks [12]. We adopt its basic concept and generalize its definition for our application. The interference range is defined as the area surrounding a receiver that is interfered with by other transmitters within it. If any transmitter is working within the area, the receiver obtains lower SINR than a given SINR threshold. Fig. 4(a) shows an example of the interference range of an MT and the transmission range of a BS. If two or more communicating stations interfere with each other, collision occurs. To avoid the collision, each transmitter should check whether there is any active receiver in its transmission range. Similarly, each receiver should check whether any active transmitter is in its interference range before starting communication.

The transmission range (or cell coverage) depends on the transmission power of a BS. However, the interference range of an MT depends on not only the transmission power of the BS but also the distance between the BS and the MT. Fig. 4(b) shows an example that depicts the interference ranges of MT 1 and MT 2 in a multi-cell environment. MT 1 is closer to BS 1 than MT 2, so it receives a stronger signal from BS 1 than MT 2 does. This means that MT 1’s interference range is smaller than that of MT 2. If a receiver has high SINR threshold, its interference range is smaller than those of other receivers with lower SINR thresholds. In this example, MT 1 has only BS 1 in its interference range, accordingly it receives negligibly small interference from neighbor cells. On the other hand, there are three neighbor BSes in the interference range of MT 2, so MT 2 suffers under much strong interference from other BSes. In our simple channel model, the interference range radius $R_T$ of an MT is defined as the following

$$R_T \leq (\eta SINR_{th})^{-1/\alpha} R$$  \hspace{1cm} (8)

where $R$ is the distance between the BS and the MT, $SINR_{th}$ is the SINR threshold, and $\alpha$ and $\eta$ are path loss exponent and the number of neighbor cells, respectively.

To determine whether a BS lies in the interference range of an MT in some neighbor cell, some assistant system is in need. For instance, if each MT is with a global positioning system (GPS), it can calculate its interference range according to its geometric location information and eq. (8). An alternative way is to use a downlink channel allocation map (DCA-MAP) that requires synchronization among BSes. The role of DCA-MAP is similar to that of downlink map (DL-MAP) in an OFDMA system [1]. While the DL-MAP is broadcasted by a BS and contains the information about downlink channel allocation, the DCA-MAP is broadcasted by each MT that transmits the pilot signal at the mapped position. Fig. 5 shows an example of frame structure in an OFDMA/TDD (time division duplexing) system. Each frame consists of downlink period and uplink period. At the beginning of downlink period, DL-MAP and uplink map (UL-MAP) are broadcasted. UL-MAP contains the information about uplink channel allocation. To make DCA-MAP use minimum resource, one subcarrier and one symbol per downlink channel are used in our design. Fig. 5 shows a case of 2 cells and 4 downlink channels. The DCA-MAP is transmitted at the beginning of uplink period. In cell 1, the downlink channels of 1, 2, and 4 are allocated, so the MTs allocated for these channels transmit the pilot signal. In cell 2, the downlink channels of 1 and 4 are used. Suppose that a new flow arrives at BS 2. Before BS 2 starts channel allocation, it determines whether it lies in the interference ranges of neighbor cell MTs from their respective DCA-MAPs. In this example, channel 3 is available because BS 1 does not use it. Regarding the possibility of allocating channel 2, more considerations are necessary. If BS 2 lies in the interference

\footnote{In uplink period, data channels, control message channels, and ranging channels are positioned. The ranging channels are used for initial random access and uplink synchronization.}
range of the MT using channel 2 in cell 1, its received pilot signal power for channel 2 is strong enough for detection, so it avoids assigning channel 2 for the new flow.

By using DCA-map and simple signalling between BSe's, a BS can estimate how much it gives interference to the MT using a particular channel. If the BS in cell $j$ allocates a channel with power of $P_j$, the SINR of MT using the channel with power of $P_i$ in cell $i$ is determined by the following.

$$SINR_i = \frac{P_i g_{ii}}{P_j g_{ij} + N_i} \simeq \frac{P_i g_{ii}}{P_j g_{ij}} = \frac{P_0 P_i g_{ii}}{P_j g_j}, \quad (9)$$

where $P_0$ is the pilot power transmitted in DCA-map, and $g_{ij} = P_i g_{ij}$ is the pilot power that the BS in cell $j$ receives. BS $j$ estimates the interference level for an MT in cell $i$ by using received DCA-map pilot power and channel allocation information from BS $i$ through the wired-line.

V. CONCLUSION

The channel allocation to achieve low inter-cell interference in multi-cell OFDMA systems is an important radio resource management issue together with power control. In this paper, we investigated channel allocation algorithms in downlink multi-cell wireless systems. Channel allocation has been a difficult problem because of the complexity in handling the inter-cell interference. In centralized approach, we proposed some heuristic algorithms and showed their performances by comparing with the optimal scheme and FRF 1 scheme in terms of complexity, throughput performance and power consumption. Compared to the optimal scheme, our PAFI and RAFI algorithms require low calculation complexity while they show similar throughput performance. They show much higher throughput and significantly lower power consumption than FRF 1 scheme. We considered a channel state estimation method and distributed channel allocation using interference range.

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