Dynamic Channel Allocation Considering the Interference Range in Multi-cell Downlink Systems

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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. In distributed channel allocation, each cell independently tries to allocate channels that suffer low interference level. In this paper, under the assumption of static users, we introduce the concept of interference range and use it in designing our two algorithms; basic and combined. The basic algorithm performs interference range detection and determines whether to use the considered channel, while the combined algorithm checks the channel quality in addition to detecting the interference range. The two algorithms dynamically perform channel allocation with low complexity and show good throughput and fairness performance.

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. 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 the channel feedback information from each MT. The transmit power can be also adjusted if the power control is possible.

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 allocates channels. 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\(^2\). 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 inner-cell interference\(^3\). In\(^4\), the concept of fractional frequency reuse was introduced and fractional frequency reuse set management algorithm was proposed. The algorithm defines non-integer frequency reuse factor and updates the reuse set dynamically. In distributed approach, the BS allocates a channel for each MT whenever requested and also considers power allocation. In\(^5\), a distributed non-cooperative game approach was used to allocate channels with minimum power consumption.

In this paper, we investigate the channel allocation problem in a multi-cell environment, and consider centralized and distributed allocation algorithms under the assumption of static users. Our algorithms measure the interference range and use it. By restricting the allocation of some channels in neighbor cells that possibly create the inter-cell interference, the considered MT can receive the signal with acceptable quality. Our distributed algorithms use the interference range for channel allocation and achieves high total throughput, low outage ratio and good fairness.

In Section II, we explain the interference range and consider it in distributed channel allocation algorithms. Numerical analysis and simulation results are given in Section III. We conclude our paper in Section IV.

### II. Channel Allocation Schemes

The use of the same channels at neighboring cells causes the inter-cell interference that lowers the system throughput. We deal with distributed channel allocation schemes where each BS allocates channels independently. Each BS and MTs can exchange some information but message overhead should be minimized. We propose two schemes and evaluate their performances.

#### 2.1. Interference range

Our schemes use the interference range in channel allocation which was originally used to deal with spatial reuse in ad hoc and sensor networks\(^6\). We adopt its basic concept and generalize its definition for our
networks. We define the interference range as the area surrounding the receiver that can be interfered by other transmitters in it. If any transmitter is working within the area, the receiver obtains lower SINR than a given SINR threshold. Fig. 1 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 depends on not only the transmission power of the BS but also the distance between the BS and the MT. Fig. 2 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 experiences much stronger interference from other BSes.

In our simple channel model, the interference range radius $R_I$ is defined as the following

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

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

To determine whether the BS lies in the interference ranges of MTs in neighbor cells, some assistant system is necessary. For instance, if each MT is with a global positioning system (GPS), it can calculate the interference range according to its geometric location information and eq. (1). An alternative way is to use a downlink channel allo-
cation 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. While the DL-MAP broadcasted by a BS 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. 3 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. The DCA-MAP needs to use the minimum resource unit. For example, one subcarrier and one symbol per downlink channel can be used for DCA-MAP. Fig. 3 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 used, so the MTs that are allocated for these channels transmit the pilot signal in the DCA-MAP. In cell 2, the downlink channels of 1 and 4 are used. Assume 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 DAC-MAPs. In this example, channel 3 is available because BS 1 does not use it either. Regarding the possibility of using channel 2, more considerations are necessary. If BS 2 lies in the interference 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.

2.2 Interference range detection
To use the interference range in channel allocation, we need an interference range detection method that is performed by each BS. Fig. 4 shows an example of message broadcasting and DCA-MAP for interference range detection. In cell 1, three channels are allocated for MTs 1, 2, and 3. The channel allocation information is delivered to neighbor BSes 2, 3, and 4 by broadcasting through the wire-line. As the broadcasting has been already used during fast handover procedures, it does not incur overhead in the current system. The channel allocation information contains channel ID, MT ID, and channel gain. If we assume the use of GPS, the broadcasting message will include the location information of each MT. Independently from the wire-line signalling, MTs transmit the pilot signal according to DCA-MAP. From the wire-line broadcasting message and DCA-MAP, each neighbor BS can decide whether it belongs to the interference ranges of neighbor cells’ MTs.

Let’s consider the case that there is a transmission in channel c at cell i and the BS in cell j wants to allocate a channel to an MT. If the BS j allocates the considered channel, the SINR of MT in cell i is given by

$$\text{SINR}_i = \frac{P_{0ji}i}{P_{0ji}i + N_i}.$$  (2)

The interference range detection at BS j depends on $\text{SINR}_i$. If $\text{SINR}_i$ is smaller than the threshold value $S_0$, BS j is considered to be in...
the interference range of the MT in cell \( i \). Thus the BS should know the channel gains \( g_{ii} \) and \( g_{ij} \) to decide whether BS \( j \) belongs to the interference range of the MT in cell \( i \). The channel gain \( g_{ii} \) between the MT in cell \( i \) and BS \( i \) is obtained through the broadcasting from BS \( i \). During the broadcasting, \( g_{ii} \) may contain an error. Assuming that the broadcasting is done frequently, we can ignore this error. The channel gain \( g_{ij} \) between the MT in cell \( i \) and BS \( j \) can be obtained from DCA-MAP received by BS \( j \). In DCA-MAP, the MT transmits the pilot signal with fixed power, so BS \( j \) can estimate \( g_{ij} \). Since there is a distance between the pilot channel in DCA-MAP and the allocated channel in frequency axis, \( g_{ij} \) contains some error according to the frequency selection. In this paper, we ignore this type of error.

Under the assumption that the noise is sufficiently small compared to the interference, \( \text{SINR}_i \) can be expressed as

\[
\text{SINR}_i = \frac{P_0 g_{ii}}{P_0 g_{ij} + N_i} \approx \frac{g_{ii}}{g_{ij}} = \frac{P_0 g_{ii}}{q_j}, \quad (3)
\]

where \( g_{ij} \) is given as \( q_j / P_0 \) and \( q_j \) is the received pilot power at BS \( j \). Then the interference range detection result is false if \( P_0 g_{ij} / q_j > S_0 \), and true otherwise. If BS \( j \) is located in the interference range of the MT in cell \( i \), the detection result is true, so BS \( j \) should not allocate the channel. Otherwise BS \( j \) can allocate it.

The weakness of channel allocation following the interference range detection is in the possibility of low channel utilization. For the channel of interest, let’s define \( P_{\text{use}} \) and \( P_{\text{det}} \) as the probabilities of the channel use and the detection result with ‘true’, respectively. If the number of neighbor cells are \( n_b \) and the traffic loads of all the cells are uniformly distributed, \( P_{\text{use}} \) can be approximately calculated by \( P_{\text{use}} \)'s and \( P_{\text{det}} \)'s of neighbor cells as follows.

\[
P_{\text{use}} = P_{\text{use}} (1 - P_{\text{det}}) + (1 - P_{\text{use}})^{n_b}
\]

\[
= (1 - P_{\text{use}} P_{\text{det}})^{n_b} \quad \text{(4)}
\]

Therefore we can obtain \( P_{\text{use}} \) by a recursive method. If BS \( j \) receives the channel allocation information from BS \( i \) according to the broadcasted messages and DCA-MAP, we obtain \( P_{\text{det}} \) as follows.

\[
P_{\text{det}} = \text{Pr} \left\{ \frac{P_0 g_{ii}}{Q_j} < S_0 \right\}, \quad (5)
\]

where \( G_{ii} = g_{ii} (x_i) \) and \( Q_j = P_0 g_{ij} (x_i) \), and \( x_i \) is the random variable vector of MTs’ locations in BS \( i \). Assuming \( g_{ii} \) and \( g_{ij} \) are time invariant, we have

\[
P_{\text{det}} = \text{Pr} \left\{ \frac{g_{ii} (x_i)}{g_{ij} (x_i)} < \frac{S_0}{x_i} \right\} = \text{Pr} \left[ x_i = x_i \right].
\]

If MTs are uniformly distributed within the cell radius \( R \) and the channel gain is determined by path loss only, we obtain

\[
P_{\text{det}} = \frac{1}{\text{Area}} \int_A I \left[ \frac{g_{ii} (x_i)}{g_{ij} (x_i)} < \frac{S_0}{x_i} \right] dx dy
\]

\[
= \frac{1}{\text{Area}} \int_A I \left\{ \frac{\sqrt{x^2 + y^2}}{(2R-x)^2+y^2} \right\}^{-\alpha} < S_0 dx dy.
\]

where \( A \) and \( \text{Area} \) are the domain of \( x_i \) and its area, respectively, and the indicator function \( I \) has 1 if the event \( B \) is true, and 0 otherwise. If the interference range detection is used, the average SINR of MTs is obtained by

\[
E[SINR_i] = \frac{1}{\text{Area}} \int_A \frac{g_{ii} (x_i) P_i P_{\text{use}}}{P_0 \sum_{j=1, j \neq i}^N g_{ij} (x_i) U_{ij} (x_i) P_{\text{use}} + N_0}
\]
where \( U_{ij}(x_i) = \begin{cases} g_{ji}(x_i) \\ g_{ij}(x_i) \end{cases} \) < \( S_0 \).

2.3. Proposed channel allocation algorithm

Firstly, we review a conventional channel allocation algorithm that uses the channel feedback information\(^\text{[8]}\). It selects a channel from unused channels and checks whether the SINR of the selected channel is greater than \( SINR_0 \). If the channel passes the test, it will be allocated.

Several algorithms belonging to this category use power control to reduce the inter-cell interference. When fixed \( P_0 \) is assumed, this type of algorithm does not have any means to count the impact of the considered channel allocation on neighbor cells. It only considers whether its own SINR is sufficiently high, so it is a selfish algorithm.

Compared to the existing algorithm, our proposed algorithm is conservative because it does not allocate the considered channel if the allocation creates severe interference to neighbor cells. Fig. 5 shows our proposed algorithm that checks the availability of the selected channel according to the interference range detection. If the selected channel is usable, the corresponding BS allocates the channel and performs the interference range signaling.

Another approach is combining the existing algorithm with our algorithm. As the selfishness of the conventional algorithm and the interference consideration of our algorithm show some complementary features, they can be combined as shown in Fig. 6. The first step checks the availability of the selected channel by considering the interference range. Then the second step tests whether the condition of the selected channel is acceptable. If the channel passes the two tests, it is allocated for the MT and the interference range information is sent to neighbor BSes. It is expected that the successful allocation ratio in our combined algorithm is smaller than those in the conventional algorithm and our basic algorithm because of the hard checking conditions. However, owing to the strict checking procedures, our combined algorithm suffers lower interference, resulting in higher SINR compared to the other schemes. Proposed algorithms need one or two comparison process, but they do not have much calculational complexity.

### Table I. MCS Level

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

### III. Numerical Results

To examine our proposed distributed algorithms, we performed simulations. In each simulation, we use a simple channel model with the path loss exponent of -4. Assume that Gaussian noise is
Fig. 6. Flow chart of combined algorithm.

Fig. 7. Example of a cell topology: 37 cells and 3 sectors per cell.

Fig. 8. Total throughput per sector. FRF 1 and FRF 3 schemes show the throughputs of 1.17Mbps and 780kbps, respectively. FRF 1 uses the whole channels so it shows good throughput performance. However, MTs that are located near the cell boundary experience the heavy interference, so they fail to have channel allocation. In FRF 3, adjacent cells use different channels, so boundary MTs have good channel conditions but the total cell throughput is much lower than that in FRF 1. The conventional scheme does not allocate a channel for an MT.

2) We have not measured the performances at the outer cells because they experience lesser and lesser interference due to the edge effect.
if the considered channel condition is not good. It reduces the inter-cell interference and achieves throughput increase by 14% compared to FRF 1 scheme. Our proposed scheme performs better than the conventional scheme, and achieves 22.3% more throughput compared to FRF 1. This is because channel allocations for cell boundary MTs in our algorithm restrict neighbor cells’ allocations of the same channels through the interference range signalling. Our combined proposal shows the best performance and achieves more throughput by 31.6% compared to FRF 1.

In Fig. 9, we count the number of available channels per sector as a measure of fairness. ‘Available’ means that the channel of interest does not experience outage (i.e., zero data rate). FRF 1 has 17.7 available channels among the allocated 21 channels. The conventional scheme and our scheme are not able to use the whole channels because some channels fail to pass the channel test. They show the results comparable to FRF 1. FRF 3 has seven available channels that equal one third of 21 channels as expected. The number of available channels is highly related to the outage ratio. Fig. 10 shows the outage ratio of allocated channels. FRF 1 shows the highest outage ratio and FRF 3 shows no outage. Our combined scheme shows lower outage compared to the conventional scheme and our basic scheme. FRF 1 suffers from high outage ratio because a channel experiences heavy interference after being allocated. This phenomenon mainly occurs to cell boundary MTs. Our basic algorithm shows the outage ratio similar to the conventional algorithm and our combined algorithm shows an acceptable low outage ratio of 1.9% at the cost of slight decrease in the number of available channels.

In Fig. 11, we observe per unit area throughput which also can be interpreted as a measure for fairness. We vary the distance between the BS and the MT. FRF 3 shows the best performance indicated by its flat curve. The performance in FRF 1 drops rapidly when the MT moves towards the cell boundary. This means that FRF 1 gains more total throughput by sacrificing cell boundary users. Thus FRF 1 shows the worst fairness performance. The conventional scheme and FRF 1 scheme show the similar tendency in terms of throughput decrease, while our two schemes achieve good fairness performance. In conclusion, these simulation results demonstrate that our combined algorithm performs best considering total throughput, outage ratio, and fairness all together.

Our schemes require some signaling overheads
compared to the conventional scheme. Each BS transmits its channel allocation state to neighbor BSes whenever channel is allocated (or withdrawn). The signaling messages are exchanged through the wired line between BSes, so it is not overhead for the wireless network. However, the pilot transmission of an MT for DCA-MAP needs wireless transmission. This overhead can be minimized through the efficient DCA-MAP design and sub-carrier selection in frequency axis.

IV. Conclusion

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. We proposed two dynamic channel allocation algorithms of ‘basic’ and ‘combined’ that use the interference range detection with low complexity. To support the interference range estimation, we considered the approach of using either GPS or uplink map. Through simulations, our proposed algorithms are compared with FRF 1, FRF 3 and the conventional algorithm. From the results, we confirmed that the combined algorithm shows high total throughput, low outage ratio, and fair channel usage. The advantage of our proposed algorithm is in supporting cell boundary MTs with good total throughput and acceptable fairness.

Reference