Joint Radio Resource Allocation and Scheduling in a Backhaul Constrained Multicell OFDMA Network

Jia Zhang, Dongfeng Yuan and Haixia Zhang

Wireless Mobile Communications and Transmission Lab (WMCT)
Shandong University, Jinan, Shandong, China, 250100
Email: zhxin913@163.com, {dfyuan, haixia.zhang}@sdu.edu.cn

Abstract—This paper addresses a joint radio resource allocation (RRA) and scheduling problem in a multi-cell OFDMA network in which the backhaul capacity is constrained. The proposed scheme is pursuing both the network utility and fairness among all users in two different levels, the intracell level and the intercell level. Analysis and simulation results suggest the proposed scheme brings better performance for the cell edge users, and manages to build cooperation links between adjacent cells without extra signal overhead for the network.

I. INTRODUCTION

The key issues that block the users in a wireless network from achieving much better performance are interference and fading. Multi-cell processing seems to have a promising ability to deal with such problems and bring dramatic improvements to the utility of the wireless network. Cooperations are supported by the backhaul links connecting the base stations from one to another, or to a central processor for some occasions.

The conventional approach to combat interference is always carried out in a single cell scenario where intercell interference is considered as noise. However, users located on each cell edge suffer the most from interference from adjacent cells which takes the main responsibility for the data rate drop and the lack of fairness for them. In this paper, a multi-cell Orthogonal Frequency Division Multiple Access (OFDMA) wireless network is considered. OFDMA technology advantages in the elimination of interference between users within one cell, and it is not as sensitive as the other multi-access schemes to the estimation errors, which makes it the most popular air-interface technique in practical systems.

Previous work has been done with the problem of RRA in both single-cell and multi-cell OFDMA systems[1][2]. When it comes to the intercell interference, a multi-cell coordination concept at the base station (BS) side is proposed which coordinate their modulation and coding schemes based on channel state information (CSI) and data streams exchange over backhaul networks[3]. All kinds of information passing through the backhaul links will cause additional signal overhead for the entire network. In practical implementations, the backhaul capacity can not be infinite [4][5], which somehow restricts the cooperation scale between the BSs. Therefore, taken additional cost on the backhaul into account, the proposed strategy only builds limited links between adjacent cells to facilitate with users who have urgent demands.

In this work, the joint radio resource allocation and scheduling scheme is performed on the minimum resource granularity by a cluster of coordinated BSs in the downlink of a wireless OFDMA network with multiple users per cell. Affected severely by the path loss fading and interferences from adjacent cells, users located near the cell edge are left with poor performance and always miss their target Quality of Service (QoS) requests. With proportional fairness [6] considerations, the proposed scheme manages to maximize the network-wide utility, and a more practical approach is considered. A limited-capacity backhaul link is established for data sharing between two cooperative BSs to eliminate the dominant interference, which in the mean time incurs additional signal overhead. This paper is trying to figure out how much improvement the cooperation can bring into the multi-cell network when backhaul constraints are presented as a major issue.

The proposed scheme is performed in two different levels, the intracell scheduling on frame level and the intercell cooperation establishment on the super-frame level. In each frame, there are a bunch of radio resource allocation units, each of which contains several consecutive subcarriers over a time slot. And a super-frame is comprised by several frames. In the intracell scheme, Hungarian algorithm[7] is used for fairness based RRA and scheduling, which offers a better chance for the suffered users on the cell edge. The intercell scheme focuses on how much signal overhead is paid for the profits gained from building the cooperation links. An approximation is made to measure the over cost on the backhaul. The intercell scheme makes sure that the selected cooperation links are still beneficial to the network utility.

The rest of the paper is organized as follows. In Section II, the problem in multi-cell scenario is brought forward. In Section III, the proposed scheme is demonstrated in two different levels. In Section IV, simulation results are presented for performance evaluation. Finally, in Section V, the conclusion for the paper is registered.

II. SYSTEM OVERVIEW

Consider a full frequency reused multi-cell OFDMA network of $K$ cells (BSs), with $M$ uniformly distributed users per cell, as shown in Fig. 1. In each cell, the smallest radio resource granularity, which consists of one subchannel combined with several continuous OFDM subcarriers over a
time slot, is referred as a radio resource allocation unit (AU). Each AU is occupied by only one user in its serving cell which guarantees that no intracell interference exists.

The channel state information (CSI) is assumed to be available to every BS in the wireless network. To describe a realistic multi-cell scenario, both small-scale rayleigh fading and large-scale path loss and shadow fading are considered[8]. Suppose that $h_{k,m}^n$ is the complex channel response from BS $k$ to user $m$ on AU $n$. Note that for the downlink, $h_{k,m}^n$ represents either an intracell or an intercell channel depends on that if user $m$ is within cell $k$ or not. Users distributed on each cell edge suffer from higher path loss from the serving BS and severer interferences from the adjacent BSs, which makes their channel quality fall far behind those who locate closer to the serving BS. Thus, it is crucial to regain fairness among all users in each cell.

In the depicted wireless network, BSs build cooperation links with their adjacent cells to share data streams in between for intercell interference coordination. In this paper, only the transmission of the shared data over the backhaul is considered as the signal overhead. Building a cooperation link from BS $k$ to BS $i$ on AU $n$ is for BS $k$ to send data streams of the user scheduled on AU $n$ in cell $k$ to BS $i$ through backhaul. It is assumed that when a cooperation link is built from BS $k$ to BS $i$, the scheduled user on AU $n$ in cell $k$ will be interference free from BS $i$ on AU $n$. In the meantime, to combat the additional signal overhead caused by building those cooperation links, the data sharing is constrained by the limited backhaul capacity. Thus, when the serving cell is enjoying the performance improvement brought by building cooperation links, it has to pay more attention to the additional cost.

On the downlink of the OFDMA network, there are two different time levels, frame level and super-frame level, on which the serving BS makes different moves accordingly. Consider the radio resource as frequency along with time, in the frequency domain, the bandwidth is divided into subchannels, while in the time domain, one frame is divided into several slots and a number of consecutive frames compose to a super-frame. Note that one AU means a subchannel over a time slot in each frame.

On AU $n$, the signal to interference plus noise ratio (SINR) received by user $m$ from its serving BS $k$ can be expressed as

$$\text{SINR}_{k,m}^n = \frac{p_k^n |h_{k,m}^n|^2}{\sum_{t=1, t \neq k}^{K} p_t^n |h_{t,m}^n|^2 + N_0}. \quad (1)$$

where $p_k^n$ represents the power spectrum for data transmissions from BS $k$ to the user scheduled on AU $n$ in its own cell under the assumption of equal power allocation, i.e., $p_k^n = P_t/N$, where $P_t$ is the total transmit power per BS and $N$ is the total number of AUs available in each frame. $N_0$ is the power spectrum of AWGN over per AU’s bandwidth. And $h_{k,m}^n$ represents the interference channel from cell $i$ to the user $m$ on AU $n$ in cell $k$.

Therefore, the instantaneous downlink rate for user $m$ scheduled on AU $n$ in cell $k$ is $r_{k,m}^n = \log_2(1 + \text{SINR}_{k,m}^n)$, and the total achieved downlink rate for user $m$ in cell $k$ will be $R_{k,m} = \sum_{n \in N_{k,m}} p_{k,m}^n$, where $N_{k,m}$ is the set of AUs occupied by user $m$ in cell $k$.

### III. PROPOSED SCHEME

The proposed scheme aims at maximizing the utility throughout the whole network. Under the constraints of backhaul capacity for every BS within the network, the RRA, user scheduling and cooperation links building must be considered jointly in order to optimize the network utility, which can be formulated as

$$\text{max} \sum_{k,m} (R_{k,m}),$$

subject to

$$R_{k,m} = \sum_{n \in N_{k,m}} \log_2(1 + \text{SINR}_{k,m}^n) \quad \forall k, m,$$

$$C_k = \sum_{n=1}^{N} N_{k,\mu} r_{k,\mu} \leq C_k^{\text{max}} \quad \forall k. \quad (2)$$

where $N_{k,\mu}^n$ is the number of cooperation links built by BS $k$ on AU $n$ in the network, and $p$ represents the scheduled user on AU $n$ of the cooperation cell. Thus, the total signal overhead in cell $k$ can be expressed in the second constraint of Eq. (2) which is limited by the maximum backhaul capacity $C_k^{\text{max}}$.

As mentioned above, based on the two time levels description of the framework, the proposed scheme could be broken into two different parts at each BS as follows.

### A. Fair Scheduling based Intracell RRA

One of the key issues in the OFDMA network is the user scheduling. The intracell scheme prepares the Hungarian algorithm to solve the joint RRA and user scheduling problem with proportional fairness considerations. The Hungarian algorithm origins from Operations Research, used as a joint
RRA and user schedule scheme, it has to be formulated as a mathematical problem first

\[
\min z = \sum_{m=1}^{M} \sum_{n=1}^{N} u_{mn} x_{mn},
\]

\[
s.t. \sum_{n=1}^{N} x_{mn} = 1, \ \forall n,
\]

\[
\sum_{m=1}^{M} x_{mn} = 1, \ \forall m,
\]

\[
x_{mn} = 0/1, \ \forall m, n.
\]

where \( U = (u_{mn})_{MN} \) stands for the utility matrix of M users and N AUs per frame for each cell. Matrix \( X = (x_{mn})_{MN} \) indicates the joint RRA and user scheduling results of applying Hungarian algorithm iteratively on the utility matrix \( U = (u_{mn})_{MN} \), where \( u_{mn} = 1 \) indicates that AU \( n \) is assigned to user \( m \) in the cell of interest.

According to the formulated problem Eq. (2), in cell \( k \), the utility matrix has to be formulated based on \( r_{kn}^{n} \). Clearly, the channel quality and the requested data rate for each user are overlooked in this scheme, and only the instantaneous data rate on each AU is considered. To meet this challenge, fairness among all users must be showed out in the utility matrix. In this work, Proportion Fairness is addressed to revise \( u_{mn} \), in cell \( k \)

\[
u_{kn}^m = r_{kn}^{n} R_{k,m}^{\text{tar}}. \tag{4}
\]

where \( R_{k,m}^{\text{tar}} \) indicates the requested data rate of each user in cell \( k \). \( R_{k,m} \) will be updated after each scheduling until it reaches its target rate \( R_{k,m}^{\text{tar}} \). The satisfied users and the allocated AUs will be removed from the utility matrix before the next scheduling begins. By iteratively performed, the intracell scheme reaches its destination when all users are satisfied or the radio resource has been run out.

\textbf{B. Cooperation Link Building}

The intracell scheme brings fairness to users in the network, it helps those who locate far away from their serving BS and those suffer from rich scattering regain a much better chance to occupy the radio resource. Unfortunately, the radio resource is easily exhausted when facing higher user requests, and the cell edge users affected severely by the interference from adjacent cells always have poorer performance, which leads to unsatisfied network performance.

To solve this dilemma, intercell interference must be reduced by introducing cooperation links between adjacent cells into the network. As elaborated before, building a cooperation link, the benefit to the network comes along with the additional signal overhead over the backhaul. It means that serious thoughts must be put into consideration when cooperation is needed for each user.

First, the question of which user should be served in the super-frame level must be answered. After the intracell scheduling, only users who can not get to their own target rates, the unsatisfied users, need the intercell cooperations.

For each unsatisfied user, its suffering can be recovered from Eq.(1). \( I_{k,m}^{n} = \sum_{i=1, i \neq k}^{K} P_{i,m}^{n}|h_{i,m}^{n}|^2 \) stands for the total interference that all the adjacent cells impose on user \( m \) in cell \( k \) on AU \( n \). Adding a cooperation link can cut one term of interference from \( I_{k,m}^{n} \) and increase the data rate, but the induced backhaul cost is neglectable. In this work, for each unsatisfied user, only the dominant interference \( DI_{k,m}^{n} \) is dealt with by building a cooperation link from its serving BS to where the dominant interference comes.

\[
DI_{k,m}^{n} = \arg \max_{i \neq k} P_{i,m}^{n}|h_{i,m}^{n}|^2. \tag{5}
\]

However, whether to perform the cooperation or not still depends on how much stress it will bring to the backhaul network. Assume that the achieved rate from intracell scheduling for a unsatisfied user \( m \) scheduled on AU \( n \) in cell \( k \) is

\[
r_{kn}^{n} = \log_2(1 + \frac{P_{i,m}^{n}|h_{i,m}^{n}|^2}{\sum_{i=1, i \neq k}^{K} P_{i,m}^{n}|h_{i,m}^{n}|^2 + N_0}). \tag{6}
\]

After performing cooperation, the dominant interference is no longer existed, which changes Eq.(6) into

\[
r_{kn}^{n} = \log_2(1 + \frac{P_{i,m}^{n}|h_{i,m}^{n}|^2}{\sum_{i=1, i \neq k}^{K} P_{i,m}^{n}|h_{i,m}^{n}|^2 + DI_{k,m}^{n} + N_0}). \tag{7}
\]

So far, the improvement can be achieved from Eq.(7) and Eq.(6). The decision of whether to build this cooperation link or not can be made if the backhaul cost can be quantified. In [4], it is said that the backhaul cost of building a cooperation link from serving cell \( k \) to the dominant interfering cell on AU \( n \) can be approximated as \( r_{k,p}^{n} \) where \( p \) is the scheduled user on AU \( n \) in the cooperative cell.

Clearly, the final benefit of building a cooperation link can be formulated as

\[
\text{benefit} = r_{kn}^{n} - r_{kn}^{n} - r_{k,p}^{n}. \tag{8}
\]

The cooperation link will be built only if \( \text{benefit} > 0 \), which assures the wireless network sees actually gains no matter how much the backhaul costs. Under the concerns of the network utility, the total backhaul capacity \( C_{\text{max}} \) also need to be fulfilled as follows

\[
\sum_{k} \sum_{n} N_{k,n} r_{k,p}^{n} \leq C_{\text{max}}. \tag{9}
\]

\textbf{IV. SIMULATION RESULTS}

Simulation results are demonstrated in this section to evaluate the proposed scheme of intracell and intercell algorithms for the multi-cell OFDMA network with maximal frequency reuse. The major parameters are outlined in Table I.

The users are distributed uniformly in each cell, and the target rates for each user in each cell are assumed to be the same.

Urban Scenario is assumed with the cell radius of 1Km, in which Rayleigh fading is for small scale fading. Pass loss and shadow fading are considered as large scale fading with
TABLE I
SIMULATION PARAMETRES

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellular Layout</td>
<td>Hexagonal with $K=7$</td>
</tr>
<tr>
<td>Cell Radius</td>
<td>1 Km</td>
</tr>
<tr>
<td>Channel Bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Users per Cell</td>
<td>$M=30$</td>
</tr>
<tr>
<td>Subcarrier Number</td>
<td>1024</td>
</tr>
<tr>
<td>Frame Length</td>
<td>10ms</td>
</tr>
<tr>
<td>Slots per Frame</td>
<td>10</td>
</tr>
<tr>
<td>AU Number per Frame</td>
<td>160</td>
</tr>
<tr>
<td>Super-Frame Length</td>
<td>30ms</td>
</tr>
<tr>
<td>Tx power per BS</td>
<td>43dBm</td>
</tr>
<tr>
<td>AWGN</td>
<td>$-100$dBm/Hz</td>
</tr>
<tr>
<td>Shadow Fading</td>
<td>$\sigma = 8$dB</td>
</tr>
<tr>
<td>Path Loss</td>
<td>$\beta_0 \approx 1.35 \times 10^{-7}$, $\gamma = 3.7$</td>
</tr>
</tbody>
</table>

Fig. 2. Average Cell Throughput against Target Rates

Fig. 3. Backhaul Cost against Target Rates

Fig. 4. Average Cell Throughput per Cell

$$\alpha_{k,m}^2 = PL_{k,m}S_{k,m},$$
where the pass loss $PL_{k,m} = \beta_0 d_{k,m}^{-\gamma}$
with $d_{k,m}$ represent the distance between BS $k$ to user $m$ and
the shadow fading $S_{k,m}$ is a log-normal random variable with
standard deviation $\sigma$.

Fig. 2 depicts how the average throughput changes under
different Quality of Service (QoS). It can be seen that
the performance of the proposed scheme with constrained
coordination lies between the full cooperation scheme where
coordination links are built for each unsatisfied user and the
none cooperation scheme where only intracell scheduling is
performed. Limited by the backhaul capacity constraints, the
proposed scheme can not bring as much improvement as the
full cooperation scheme. The growth of all three curves tends
to be slowdown as the QoS increase, which is because the
radio resource is running out.

Fig. 3 shows the backhaul costs of the two schemes demonstrated in Fig. 2. It seems that the full cooperation scheme paid too much price for the performance improvement. On the contrary, the proposed scheme remains the benefits brought by cooperation.

The curves in Fig. 4 describe how the fairness guarantees worked for the users distributed in different positions within one cell. It can be observed that there exists a much larger difference of the users’ performance from the ones near the serving BS and the ones located on cell edge when no fairness scheme is performed. And the proposed scheme brings the best fairness among all users as the theoretical analysis predicted. The Jain’s Fairness Index[9] is calculated accordingly. The proposed scheme reaches 0.806, which is proved to be the best fairness schedule in this work.

V. CONCLUSION

In this piece of work, a joint radio resource allocation and scheduling scheme is investigated in a multi-cell OFDMA network where the backhaul capacity is constrained. There are two levels for the proposed scheme, both of which are carried out by BSs in the network. The intracell scheduling is solved by the Hungarian algorithm based on proportional fairness while the intercell cooperation scheme manages to select the cooperation links which only bring benefit to the network utility under limited backhaul costs. Simulation results suggest the proposed scheme brings fairness improvement to users all
over the network, especially the ones on the cell edge. And without extra signal overhead, cooperation between adjacent cells can still be beneficial.

ACKNOWLEDGMENT

The work presented in this article was supported in part by the research grant from National Science foundation of China with number No.61071122, No.60972043 and the open research fund of National Mobile Communication Research Lab., Southeast University, China.

REFERENCES