Adaptive Resource Allocation for MC-CDMA and OFDMA in Reconfigurable Radio Systems

Yonghoon Choi

This paper studies the uplink resource allocation for multiple radio access (MRA) in reconfigurable radio systems, where multiple-input and multiple-output (MIMO) multicarrier-code division multiple access (MC-CDMA) and MIMO orthogonal frequency-division multiple access (OFDMA) networks coexist. By assuming multi-radio user equipment with network-guided operation, the optimal resource allocation for MRA is analyzed as a cross-layer optimization framework with and without fairness consideration to maximize the uplink sum-rate capacity. Numerical results reveal that parallel MRA, which uses MC-CDMA and OFDMA networks concurrently, outperforms the performance of each MC-CDMA and OFDMA network by exploiting the multiuser selection diversity.

Keywords: MC-CDMA, multiple radio access, OFDMA, reconfigurable radio systems, resource allocation.

Manuscript received Aug. 25, 2013; revised Nov. 21, 2013; accepted Dec. 16, 2013.

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2013R1A1A2061292).

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I. Introduction

An exponential growth in mobile data traffic, which is driven by the use of wireless devices such as smartphones and tablet PCs, is placing an increasing demand on Internet service providers to provide higher rates of data transmission. To deal with this demand, various issues have been discussed in heterogeneous cellular networks [1]. Among these networks, one of the promising candidates for the provision of higher rates of data transmission is the cognitive wireless network (CWN) [2], whose main feature is that it allows for the coexistence of multiple radio access networks (RANs). In a CWN, multi-radio user equipment (MUE) can choose a suitable RAN with various supported radio access technologies (RATs) [2]. This reconfigurable radio system using multiple RATs has been studied within the framework of software-defined radio and cognitive radio in recent years [3]. For a radio enabler in this system, a cognitive pilot channel is used for spectrum awareness and radio resource management [4]. From the viewpoint of signaling overhead, Yagyu and others [5] show that the increase of control overhead is not significant even in carrier aggregation deployment scenarios.

There have been several studies on the concurrent use of multiple RANs in heterogeneous cellular networks. Lo and others [6] present a comparison of the potential maximum sum capacity of downlink multiple-input and multiple-output (MIMO) multicarrier-code division multiple access (MC-CDMA) and MIMO orthogonal frequency-division multiple access (OFDMA) in a single-cell multiuser environment. For OFDMA-based multiple RANs, an uplink joint resource allocation for parallel multiple radio access (MRA) is investigated in [7], where OFDMA-based multiple RATs are used at the same time for data transmission. However, the parallel MRA of MC-CDMA and OFDMA is not considered in [6], and the case of heterogeneous cellular networks (that is, when there exist MC-CDMA and OFDMA networks simultaneously) is not investigated in [7]. Hence, it is the right time to explore the uplink resource allocation problem for parallel MRA in heterogeneous cellular networks, where MIMO MC-CDMA and MIMO OFDMA networks coexist.

This paper considers the maximization of the sum-rate capacity in an uplink CWN system, which employs MIMO OFDMA and MIMO MC-CDMA networks as a subsystem. Use of Karush–Kuhn–Tucker (KKT) conditions, for obtaining an optimal solution, means we are able to find a new efficient channel and power-allocation algorithm. This algorithm uses both a water-filling and a bisection method, where the problem being solved is really that of network-guided operation.

The rest of this paper is organized as follows. Section II introduces the reconfigurable radio system model and explains the channel structure of each OFDMA and MC-CDMA system. In Section III, the problem of maximizing the sum capacity for the system model is formulated. Numerical analysis for optimal user selection and resource allocation is provided in Section IV. Section V presents the numerical results of the reconfigurable radio system. Finally, Section VI concludes the paper.

II. System Model

This system model is based on [6], which uses a switched MRA scheme among available RATs, where only one RAT is used alternatively for data transmission in the downlink case. However, our proposed system model uses a parallel MRA scheme, where multiple RATs are utilized concurrently in the uplink case. Figure 1(a) describes a reconfigurable radio system model, where different type of RANs can be used concurrently to transmit data in the uplink. Each RAN, with its access point (AP) having similar coverage to that of other RANs, has a different channel-gain link between its AP and MUEs. Each MUE can access multiple RANs simultaneously. Figure 1(b) shows the channel structure for analysis, which is based on [6]. This model divides the whole channel into a number of flat-fading subcarriers, which are further grouped into N_B sub-bands, each containing N_S subcarriers. The sub-band size is within the coherence bandwidth. Therefore, every subcarrier in a sub-band has the same channel gain. The AP has N_R receive antennas, while the MUE has N_T transmit antennas; thus, put together they form a MIMO channel characterized by an $N_R \times N_T$ matrix, H_{kb}, for every subcarrier within sub-band b of user k.

This channel structure, based on [6], can be used in different ways within different RANs as follows:

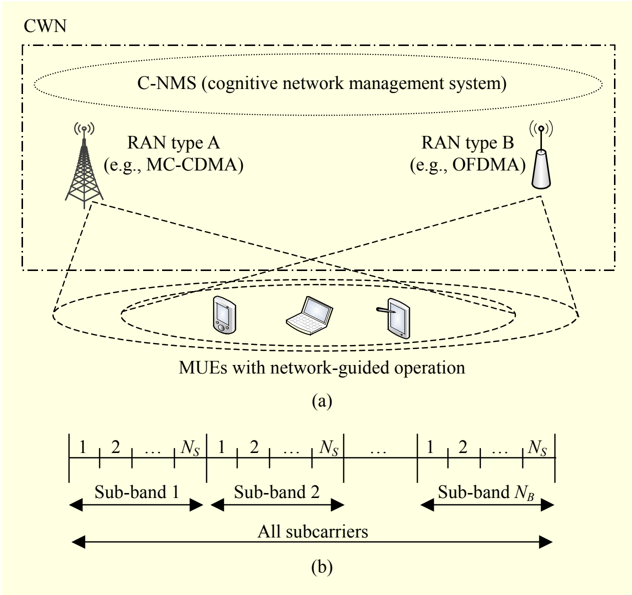

Fig. 1. Reconfigurable radio system model: (a) heterogeneous environment of OFDMA and MC-CDMA and (b) channel structure.

- The users (or MUEs, alternatively) of an OFDMA system are divided by different sets of subcarriers. Hence, the transmit signal resembles a single-user's situation, which is for the assigned subcarrier c in sub-band b.
- In an MC-CDMA system, each and every subcarrier is simultaneously shared between several users. This system assumes that each symbol is spread with an orthogonal code over one sub-band and that the channel is flat within each sub-band. And, perfect synchronization at the bit and chip levels is assumed in the system model. Thus, both the intra- and inter-user interference can be set to zero. Each user's transmit signals are multiplexed by both spatial signatures and spreading codes within a sub-band. More than one code channel can be occupied by a user, and the number of codes available is equal to the number of subcarriers within a sub-band, which leads to a total number of $N_{\tilde{S}}$ codes, each with length $N_{\tilde{S}}$ chips.

III. Problem Formulation

This work investigates the maximum sum capacity[1)] to explore uplink resource allocation for parallel MRA, which considers the optimal joint user selection (that is, subcarrier or

1) The maximum average sum capacity is expressed as $C^{\text{ergodic}} = \max\ E\left\{\sum_{k=1}^{K} R_k(t)\right\}$, where $R_{k(t)}$ is the instantaneous rate function of user k at time t, which represents the number of bits per symbol transmitted. This can be achieved by maximizing the instantaneous sum rate $C^{\text{inst}} = \max\left\{\sum_{k=1}^{K} R_k(t)\right\}$.

http://dx.doi.org/10.4218/etrij.14.0113.0843

code allocation) and power allocation.

Only one user of the OFDMA system can occupy every subcarrier. Hence, the rate of user k [5] is

$$R_k^{\text{OFDMA}} = N_S \sum_{b=1}^{N_B} \rho(k,b) \sum_{p=1}^{N_P} \log_2\left(1+\gamma_{kb}^{(p)} \frac{P_{kb}^{(p)}}{N_S}\right), \tag{1}$$

where $\gamma_{kb}^{(p)}$ and $P_{kb}^{(p)}$ are the effective channel-gain-to-interference-plus-noise ratio (that is, with white inter-cell interference) and the power of the user k on sub-band b and spatial channel p, respectively. Selecting spatially separated antennas determines the spatial channel p for each subcarrier. The number of available spatial channels, N_P, is bounded by min (N_T, N_R). The indicator function $\rho(k,b) \in \{0,1\}$ is equal to one in the case of a sub-band b where OFDMA is being allocated to user k and is equal to zero otherwise.

A user of the MC-CDMA system occupies the whole spectrum. Therefore, the rate of user k is expressed as

$$R_k^{\text{CDMA}} = \sum_{\tilde{c}=1}^{N_{\tilde{S}}} \rho(k,\tilde{c}) \sum_{\tilde{b}=1}^{N_{\tilde{B}}} \sum_{\tilde{p}=1}^{N_{\tilde{P}}} \log_2\left(1+\gamma_{k\tilde{b}}^{(\tilde{p})} P_{k\tilde{b}\tilde{c}}^{(\tilde{p})}\right), \tag{2}$$

where $P_{k\tilde{b}\tilde{c}}^{(\tilde{p})}$ is the power spent of user k on sub-band $\tilde{b}$ and spatial channel $\tilde{p}$ with code channel $\tilde{c}$. The indicator function $\rho(k,\tilde{c}) \in \{0,1\}$ is equal to one in the case of a code channel $\tilde{c}$ where MC-CDMA is being allocated to user k and is equal to zero otherwise.

In a CWN, a user can access OFDMA and MC-CDMA systems simultaneously. Thus, the rate of user k can be expressed as

$$R_k^{\text{CWN}} = R_k^{\text{OFDMA}} + R_k^{\text{CDMA}}. \tag{3}$$

Therefore, the optimization problem can be written as

$$C^{\text{CWN}} = \max_{\left\{\substack{\rho(k,b)\in\{0,1\},\\ P_{kb}^{(p)}\ge 0,\\ \rho(k,\tilde{c})\in\{0,1\},\\ P_{k\tilde{b}\tilde{c}}^{(\tilde{p})}\ge 0}\right\}} \left(\sum_{k=1}^{K} R_k^{\text{OFDMA}} + \sum_{k=1}^{K} R_k^{\text{CDMA}}\right) \tag{4}$$

subject to

$$\sum_{k=1}^{K} \rho(k,b) = 1 \qquad \forall b \in \{1, 2, \ldots, N_B\}, \tag{5}$$

$$\sum_{k=1}^{K} \rho(k,\tilde{c}) = 1 \qquad \forall \tilde{c} \in \{1, 2, \ldots, N_{\tilde{S}}\}, \tag{6}$$

and

$$\sum_{b=1}^{N_B} \sum_{p=1}^{N_P} P_{kb}^{(p)} + \sum_{\tilde{c}=1}^{N_{\tilde{S}}} \sum_{\tilde{p}=1}^{N_{\tilde{P}}} \sum_{\tilde{b}=1}^{N_{\tilde{B}}} P_{k\tilde{b}\tilde{c}}^{(\tilde{p})} = P_k^T \qquad \forall k; \tag{7}$$

where K is the total number of users and P_k^T is the total power of the user k.

IV. Optimal User Selection and Resource Allocation

1. Optimal Solution

Given the total power constraint of (7), the optimal user assignment for a channel depends on the user assignment in other channels. The formulation described in (4) is combinatorial; hence, the concept of time-sharing is necessary [8]. The time-sharing factors of [8] mean that the ranges of $\rho(k,b) \in \{0,1\}$ and $\rho(k,\tilde{c}) \in \{0,1\}$ are relaxed to real numbers within the interval [0, 1].

Relaxing the constraints, we can rewrite the optimization problem as

$$C^{\text{CWN}} = \max_{\left\{\substack{\rho(k,b)\in[0,1],\\ s_{kb}\in[0,\infty),\\ \rho(k,\tilde{c})\in[0,1],\\ s_{k\tilde{c}}\in[0,\infty)}\right\}} \left\{\sum_{b=1}^{N_B} \sum_{k=1}^{K} \rho(k,b) C_{kb}\left(\frac{s_{kb}}{\rho(k,b)}\right) + \sum_{\tilde{c}=1}^{N_{\tilde{S}}} \sum_{k=1}^{K} \rho(k,\tilde{c}) C_{k\tilde{c}}\left(\frac{s_{k\tilde{c}}}{\rho(k,\tilde{c})}\right)\right\} \tag{8}$$

subject to

$$\sum_{b=1}^{N_B} s_{kb} + \sum_{\tilde{c}=1}^{N_{\tilde{S}}} s_{k\tilde{c}} = P_k^T \qquad \forall k, \tag{9}$$

where

$$s_{kb} = \rho(k,b) P_{kb} \quad \text{with } P_{kb} = \sum_{p=1}^{N_P} P_{kb}^{(p)}, \tag{10}$$

$$C_{kb}(P_{kb}) = \max_{\left\{\sum_{p=1}^{N_P} P_{kb}^{(p)} = P_{kb}\right\}} N_S \sum_{p=1}^{N_P} \log_2\left(1+\gamma_{kb}^{(p)} \frac{P_{kb}^{(p)}}{N_S}\right), \tag{11}$$

$$s_{k\tilde{c}} = \rho(k,\tilde{c}) P_{k\tilde{c}} \quad \text{with } P_{k\tilde{c}} = \sum_{\tilde{b}=1}^{N_{\tilde{B}}} \sum_{\tilde{p}=1}^{N_{\tilde{P}}} P_{k\tilde{b}\tilde{c}}^{(\tilde{p})}, \tag{12}$$

and

$$C_{k\tilde{c}}(P_{k\tilde{c}}) = \max_{\left\{\sum_{\tilde{b}=1}^{N_{\tilde{B}}} \sum_{\tilde{p}=1}^{N_{\tilde{P}}} P_{k\tilde{b}\tilde{c}}^{(\tilde{p})} = P_{k\tilde{c}}\right\}} \sum_{\tilde{b}=1}^{N_{\tilde{B}}} \sum_{\tilde{p}=1}^{N_{\tilde{P}}} \log_2\left(1+\gamma_{k\tilde{b}}^{(\tilde{p})} P_{k\tilde{b}\tilde{c}}^{(\tilde{p})}\right). \tag{13}$$

Since $\rho(k,b) C_{kb}\left(\frac{s_{kb}}{\rho(k,b)}\right)$ and $\rho(k,\tilde{c}) C_{k\tilde{c}}\left(\frac{s_{k\tilde{c}}}{\rho(k,\tilde{c})}\right)$ in (8) are concave with respect to $(\rho(k,b), s_{kb})$ and $(\rho(k,\tilde{c}), s_{k\tilde{c}})$, respectively (because all constraints are linear functions), the above formulation becomes a convex problem. This means that an optimal solution can be obtained as a global maximum. For uplink resource optimality, the Lagrangian is

$$
\begin{aligned}
&L\left\{s_{kb},\ \rho(k,b),\ s_{k\tilde{c}},\ \rho(k,\tilde{c}),\ \beta_b,\ \beta_{\tilde{c}},\ \alpha_k\right\} \\
&= \sum_{b=1}^{N_B}\sum_{k=1}^{K}\rho(k,b)C_{kb}\left(\frac{s_{kb}}{\rho(k,b)}\right) \\
&+ \sum_{\tilde{c}=1}^{N_{\tilde{S}}}\sum_{k=1}^{K}\rho(k,\tilde{c})C_{k\tilde{c}}\left(\frac{s_{k\tilde{c}}}{\rho(k,\tilde{c})}\right) \\
&- \sum_{b=1}^{N_B}\beta_b\left(\sum_{k=1}^{K}\rho(k,b)-1\right) - \sum_{\tilde{c}=1}^{N_{\tilde{S}}}\beta_{\tilde{c}}\left(\sum_{k=1}^{K}\rho(k,\tilde{c})-1\right) \\
&- \sum_{k=1}^{K}\alpha_k\left(\sum_{b=1}^{N_B}s_{kb}+\sum_{\tilde{c}=1}^{N_{\tilde{S}}}s_{k\tilde{c}}-P_k^T\right),
\end{aligned}
\tag{14}
$$

where β_b, $\beta_{\tilde{c}}$, and α_k are the Lagrange multipliers for the constraints (5), (6), and (9), respectively. To obtain the necessary conditions for the optimal solution *, differentiating $L\{s_{kb},\ \rho(k,b),\ s_{k\tilde{c}},\ \rho(k,\tilde{c}),\ \beta_b,\ \beta_{\tilde{c}},\ \alpha_k\}$ with respect to $\{s_{kb},\ \rho(k,b),\ s_{k\tilde{c}},\ \rho(k,\tilde{c})\}$, respectively, provides the following KKT conditions:

$$
\begin{aligned}
&\left.\frac{\partial L}{\partial s_{kb}}\right|_{(s_{kb},\ \rho(k,b))=(s_{kb}^*,\ \rho^*(k,b))} \\
&= C'_{kb}\left(\frac{s_{kb}^*}{\rho^*(k,b)}\right)-\alpha_k = \begin{cases} <0 & s_{kb}^*=0, \\ =0 & s_{kb}^*\in(0,\infty), \end{cases}
\end{aligned}
\tag{15}
$$

$$
\begin{aligned}
&\left.\frac{\partial L}{\partial \rho(k,b)}\right|_{(s_{kb},\ \rho(k,b))=(s_{kb}^*,\ \rho^*(k,b))} \\
&= \left(C_{kb}\left(\frac{s_{kb}^*}{\rho^*(k,b)}\right)-\frac{s_{kb}^*}{\rho^*(k,b)}C'_{kb}\left(\frac{s_{kb}^*}{\rho^*(k,b)}\right)\right)-\beta_b \\
&= \begin{cases} >0 & \rho^*(k,b)=1, \\ =0 & \rho^*(k,b)\in(0,\ 1), \\ <0 & \rho^*(k,b)=0, \end{cases}
\end{aligned}
\tag{16}
$$

$$
\begin{aligned}
&\left.\frac{\partial L}{\partial s_{k\tilde{c}}}\right|_{(s_{k\tilde{c}},\ \rho(k,\tilde{c}))=(s_{k\tilde{c}}^*,\ \rho^*(k,\tilde{c}))} \\
&= C'_{k\tilde{c}}\left(\frac{s_{k\tilde{c}}^*}{\rho^*(k,\tilde{c})}\right)-\alpha_k = \begin{cases} <0 & s_{k\tilde{c}}^*=0, \\ =0 & s_{k\tilde{c}}^*\in(0,\infty), \end{cases}
\end{aligned}
\tag{17}
$$

and

$$
\begin{aligned}
&\left.\frac{\partial L}{\partial \rho(k,\tilde{c})}\right|_{(s_{k\tilde{c}},\ \rho(k,\tilde{c}))=(s_{k\tilde{c}}^*,\ \rho^*(k,\tilde{c}))} \\
&= \left(C_{k\tilde{c}}\left(\frac{s_{k\tilde{c}}^*}{\rho^*(k,\tilde{c})}\right)-\frac{s_{k\tilde{c}}^*}{\rho^*(k,\tilde{c})}C'_{k\tilde{c}}\left(\frac{s_{k\tilde{c}}^*}{\rho^*(k,\tilde{c})}\right)\right)-\beta_{\tilde{c}} \\
&= \begin{cases} >0 & \rho^*(k,\tilde{c})=1, \\ =0 & \rho^*(k,\tilde{c})\in(0,\ 1), \\ <0 & \rho^*(k,\tilde{c})=0, \end{cases}
\end{aligned}
\tag{18}
$$

where, for (15)–(18), $\alpha_k,\ \beta_b,\ \beta_{\tilde{c}}\ \geq 0\quad \forall k,\ b,\ \tilde{c}$.

By using (16) and (18), one can obtain the optimal user assignment k for sub-band b for OFDMA and code channel $\tilde{c}$ for MC-CDMA when the following is maximized for the optimal value α_k:

$$
\begin{aligned}
H_{kb}(\alpha_k) &= C_{kb}\left(C_{kb}^{\prime -1}(\alpha_k)\right) \\
&\quad -\alpha_k C_{kb}^{\prime -1}(\alpha_k) \quad \text{for OFDMA,}
\end{aligned}
\tag{19}
$$

$$
\begin{aligned}
H_{k\tilde{c}}(\alpha_k) &= C_{k\tilde{c}}\left(C_{k\tilde{c}}^{\prime -1}(\alpha_k)\right) \\
&\quad -\alpha_k C_{k\tilde{c}}^{\prime -1}(\alpha_k) \quad \text{for MC-CDMA,}
\end{aligned}
\tag{20}
$$

where α_k is chosen by using a gradient-based search for (9), and $C^{-1}(.)$ represents the inverse mapping function of C. For the optimal user assignment k in the CWN, (9) can be expressed as

$$
\sum_{b=1}^{N_B}\rho(k,b)C_{kb}^{\prime -1}(\alpha_k)+\sum_{\tilde{c}=1}^{N_{\tilde{S}}}\rho(k,\tilde{c})C_{k\tilde{c}}^{\prime -1}(\alpha_k)=P_k^T. \tag{21}
$$

Intuitively, (19) and (20) implies a power efficiency measure because the user assignment k^* with the maximum $H_{kb}(\alpha_k)$ and $H_{k\tilde{c}}(\alpha_k)$ represents the most efficient power use for maximizing its total throughput on sub-band b and on code channel $\tilde{c}$ for a given α_k.

By using $P_{kb}^* = C_{kb}^{\prime -1}(\alpha_k)$ and $P_{k\tilde{c}}^* = C_{k\tilde{c}}^{\prime -1}(\alpha_k)$ from the KKT conditions, the power constraint can be expressed in terms of the water level (λ_k) as

$$
\begin{aligned}
H_{kb}(\lambda_k) &= C_{kb}\left(P_{kb}^*\right) \\
&\quad -\left(\lambda_k \ln 2\right)^{-1}P_{kb}^* \quad \text{for OFDMA,}
\end{aligned}
\tag{22}
$$

$$
\begin{aligned}
H_{k\tilde{c}}(\lambda_k) &= C_{k\tilde{c}}\left(P_{k\tilde{c}}^*\right) \\
&\quad -\left(\lambda_k \ln 2\right)^{-1}P_{k\tilde{c}}^* \quad \text{for MC-CDMA,}
\end{aligned}
\tag{23}
$$

where $\alpha_k = \left(\lambda_k \ln 2\right)^{-1}$, and

$$
P_{kb}^*(\lambda_k) = N_S\sum_{p=1}^{N_P}\left[\lambda_k-\frac{1}{\gamma_{kb}^{(p)}}\right]^+ \quad \text{for OFDMA,} \tag{24}
$$

$$
P_{k\tilde{c}}^*(\lambda_k) = \sum_{\tilde{p}=1}^{N_{\tilde{P}}}\sum_{\tilde{b}=1}^{N_{\tilde{B}}}\left[\lambda_k-\frac{1}{\gamma_{k\tilde{b}}^{(\tilde{p})}}\right]^+ \quad \text{for MC-CDMA,} \tag{25}
$$

with $[z]^+ = \max\{z,\ 0\}$. Therefore, the optimal user assignment set is given by

$$
k^*(b,\tilde{c}) = \arg\max_k\left\{H_{kb}(\lambda_k)+H_{k\tilde{c}}(\lambda_k)\right\},\ \forall b,\ \tilde{c} \tag{26}
$$

and the optimal λ_k is achieved under the condition of (21).

2. Proposed Algorithm

This paper proposes the following algorithm for finding the optimal solution by using the bisection method.[2)]

Step 1. Initialize the water level λ_k (> 0).

Set $\lambda_k^l = 0$ where λ_k^l is the lower limit.

Step 2. Compute γ_{kb}, P_{kb} for OFDMA, and $\gamma_{k\tilde{b}}, P_{k\tilde{c}}$ for MC-CDMA.

Step 3. Select the optimal user $k^*(b,\tilde{c})$ according to (26).

Step 4. Evaluate the power constraint of (21) and update λ_k.

IF $\sum_b P^*_{k^*(b,\tilde{c})b}(\lambda_k) + \sum_{\tilde{c}} P^*_{k^*(b,\tilde{c})\tilde{c}}(\lambda_k) < P_k^T$, then

Set $\lambda_k^l = \lambda_k$ and $\lambda_k \leftarrow 2 \times \lambda_k$.

Go back to Step 3.

Else

Set $\lambda_k^u = \lambda_k$ where λ_k^u is the upper bound.

End

Step 5. Adjust λ_k until the error tolerance ε is satisfied as below:

While $\left(\left| \sum_b P^*_{k^*(b,\tilde{c})b}(\lambda_k) + \sum_{\tilde{c}} P^*_{k^*(b,\tilde{c})\tilde{c}}(\lambda_k) - P_k^T \right| > \varepsilon \right)$

Set $\lambda_k = \dfrac{\left(\lambda_k^l + \lambda_k^u\right)}{2}$ and compute the optimal $k^*(b,\tilde{c})$ according to (26).

IF $\sum_b P^*_{k^*(b,\tilde{c})b}(\lambda_k) + \sum_{\tilde{c}} P^*_{k^*(b,\tilde{c})\tilde{c}}(\lambda_k) < P_k^T$, then

Set $\lambda_k^l = \lambda_k$.

Else if $\sum_b P^*_{k^*(b,\tilde{c})b}(\lambda_k) + \sum_{\tilde{c}} P^*_{k^*(b,\tilde{c})\tilde{c}}(\lambda_k) > P_k^T$

Set $\lambda_k^u = \lambda_k$.

End

End

3. Consideration of Fairness

To consider the fairness, some additional constraints are imposed on (8) and (9) as follows:

$$\sum_{b=1}^{N_B} \rho(k,b) \le \rho_{k,\max} \quad \forall k \text{ for OFDMA} \tag{27}$$

and

$$\sum_{\tilde{c}=1}^{N_{\tilde{S}}} \rho(k,\tilde{c}) \le \tilde{\rho}_{k,\max} \quad \forall k \text{ for MC-CDMA}, \tag{28}$$

where $\rho_{k,\max}$ and $\tilde{\rho}_{k,\max}$ are the maximum number of sub-bands and code channels user k can occupy, respectively. When the fairness is considered, the Lagrangian of (14) can be changed as below

$$\begin{aligned} L = &\sum_{b=1}^{N_B}\sum_{k=1}^{K} \rho(k,b) C_{kb}\left(\frac{s_{kb}}{\rho(k,b)}\right) \\ &+ \sum_{\tilde{c}=1}^{N_{\tilde{S}}}\sum_{k=1}^{K} \rho(k,\tilde{c}) C_{k\tilde{c}}\left(\frac{s_{k\tilde{c}}}{\rho(k,\tilde{c})}\right) \\ &- \sum_{b=1}^{N_B} \beta_b \left(\sum_{k=1}^{K} \rho(k,b) - 1\right) - \sum_{\tilde{c}=1}^{N_{\tilde{S}}} \beta_{\tilde{c}} \left(\sum_{k=1}^{K} \rho(k,\tilde{c}) - 1\right) \\ &- \sum_{k=1}^{K} \alpha_k \left(\sum_{b=1}^{N_B} s_{kb} + \sum_{\tilde{c}=1}^{N_{\tilde{S}}} s_{k\tilde{c}} - P_k^T\right) \\ &- \sum_{k=1}^{K} \varphi_k \left(\sum_{b=1}^{N_B} \rho(k,b) - \rho_{k,\max}\right) \\ &- \sum_{k=1}^{K} \tilde{\varphi}_k \left(\sum_{\tilde{c}=1}^{N_{\tilde{S}}} \rho(k,\tilde{c}) - \tilde{\rho}_{k,\max}\right), \end{aligned} \tag{29}$$

where φ_k and $\tilde{\varphi}_k$ are the Lagrange multipliers.

Since the additional constraints are linear functions, the KKT conditions give the power constraint of (22) and (23) as below

$$\begin{aligned} H_{kb}(\lambda_k) = &C_{kb}\left(P_{kb}^*\right) \\ &-\left(\lambda_k \ln 2\right)^{-1} P_{kb}^* - \varphi_k \quad \text{for OFDMA}, \end{aligned} \tag{30}$$

$$\begin{aligned} H_{k\tilde{c}}(\lambda_k) = &C_{k\tilde{c}}\left(P_{k\tilde{c}}^*\right) \\ &-\left(\lambda_k \ln 2\right)^{-1} P_{k\tilde{c}}^* - \tilde{\varphi}_k \quad \text{for MC-CDMA}. \end{aligned} \tag{31}$$

By using (30) and (31), the optimal user assignment k^* can be explored with (26).

V. Numerical Results

1. Simulation Environments

The system model based on [6] is investigated for uplink optimal resource allocation with and without the fairness constraint in a single-cell (or equivalently, multi-cell with white inter-cell interference) environment, where fairness is modeled by a maximum number of allowable allocated channels for each user. The users are uniformly distributed over a shared region comprising hexagonal cells of radius 1 km, with the APs located at the left and right edges of the shared region. The simulation environment considers a frequency-selective fading channel and models it as an exponential power delay profile with each tap experiencing independent and identically distributed Rayleigh fading. Without loss of generality, shadowing is excluded, while the path loss effect is considered as $P_k = P_0 \left(d_k / d_0\right)^{-\delta}$ for $d_k \ge d_0$, where P_k is the average power of user k at distance d_k, P_0 is the average received power at d_0, and δ is the path loss exponent. Every user has the same P_0 for $d_k < d_0$ (d_0 = 100 m). The detailed simulation parameters are summarized in Table 1. It is assumed that the queue for every user is full and that no delay constraint is considered.

2) There are different methods (e.g., Newton's method, golden section search, etc.) to find an optimal solution. In general, there exists a trade-off between the converging speed and robustness of the solution.

Table 1. Simulation parameters and assumptions for uplink analysis, which is based on [6].

MC-CDMA and OFDMA parameter	
Total number of subcarriers	1,024
Maximum spreading factor (N_S)	32
Number of sub-bands (N_B)	32
Number of antennas ($N_R = N_T$)	2
Power delay profile	Exponential (i.i.d. Rayleigh)
Maximum delay (τ_{max})	160 samples
rms delay (τ_{rms})	16 samples
Cell parameter	
Total transmit power (P_k^T)	10 dBm/MHz
Average received power	–20 dBm/MHz (at 100 m)
Noise power PSD	–40 dBm/MHz
Average SNR/subcarrier	20 dB (at 100 m)
Path-loss exponent	3
Constraint of maximum allowable channels per user	
For 2, 4, 8, 16, and 32 users, respectively	16, 8, 4, 2, 1, and respectively

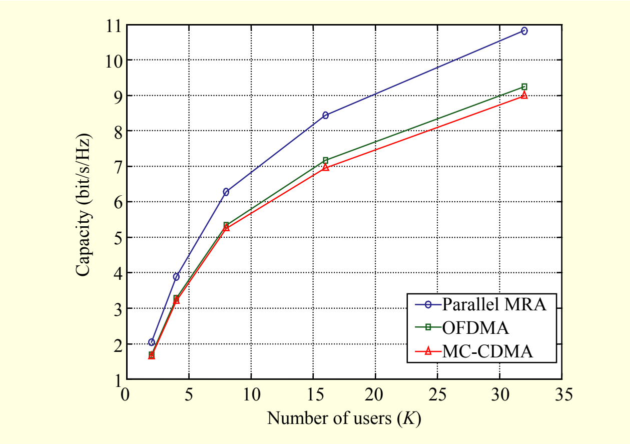

Fig. 2. Comparison of average sum capacity.

2. Simulation Results

The sum capacity of the parallel MRA is compared with each OFDMA and MC-CDMA system in Fig. 2, where multiple antennas (that is, $N_R = N_T = 2$) are applied in the CWN system model. In all cases, the sum capacities of the parallel MRA are better than each system, and the parallel MRA achieves more capacity increase (approximately 15%) with the number of users. The reason for this is because the parallel MRA achieves a more efficient exploitation of multiuser diversity.

The effect of the fairness constraint on the sum capacity is evaluated in Fig. 3. This result shows a different behavior to that of the capacity gap when the fairness constraint is applied to MC-CDMA, OFDMA, and parallel MRA. This means that significant capacity decreases and a broadened capacity gap are due to the fairness constraint. The two-antenna configuration achieves more than a three-fold decrease. This indicates that a consideration of fairness affects the capacity loss of the systems, which is crucial for practical system settings.

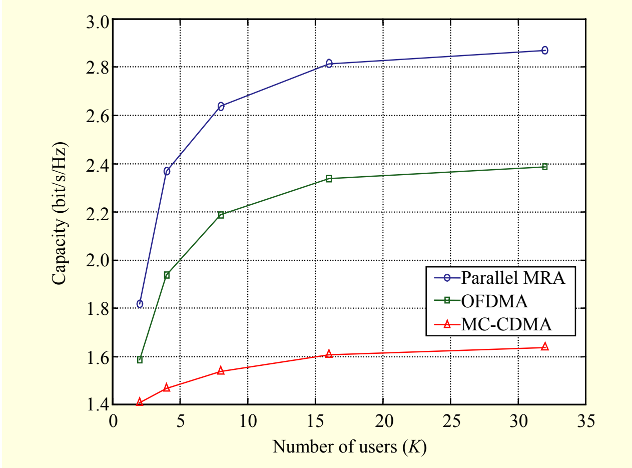

Fig. 3. Comparison of average sum capacity with maximum channel constraint.

VI. Conclusion

This paper analyzed the adaptive resource allocation for MRA in reconfigurable radio systems, where MC-CDMA and OFDMA networks coexist. The proposed algorithm exploited users who utilize the power most efficiently for both network accesses. Numerical results demonstrated that the parallel MRA (that is, concurrent use of MC-CDMA and OFDMA systems) outperforms the performance of each system because of the superiority in exploiting the multiuser selection diversity over the frequency domain.

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