Interference-Aware Downlink Resource Management for OFDMA Femtocell Networks

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Abstract

Femtocell is an economical solution to provide high speed indoor communication instead of the conventional macro-cellular networks. Especially, OFDMA femtocell is considered in the next generation cellular network such as 3GPP LTE and mobile WiMAX system. Although the femtocell has great advantages to accommodate indoor users, interference management problem is a critical issue to operate femtocell network. Existing OFDMA resource management algorithms only consider optimizing system-centric metric, and cannot manage the co-channel interference. Moreover, it is hard to cooperate with other femtocells to control the interference, since the self-configurable characteristics of femtocell. This paper proposes a novel interference-aware resource allocation algorithm for OFDMA femtocell networks. The proposed algorithm allocates resources according to a new objective function which reflects the effect of interference, and the heuristic algorithm is also introduced to reduce the complexity of the original problem. The Monte-Carlo simulation is performed to evaluate the performance of the proposed algorithm compared to the existing solutions.

Keywords: OFDMA femtocell, interference management, resource allocation

1. Introduction

The growth of the indoor communications has overloaded the conventional macrocellular systems. Recent surveys present that 50 percent of phone calls and 70 percent of data services will be happened indoors. In the next generation systems, more intelligent devices will be appeared, and contents of services are heavier than the services in current world. Since extending coverage and providing quality of ser vice (QoS) for indoor users require expensive costs to the macrocells, it becomes necessary to develop more efficient solutions for the indoor services [1].

Femtocells, known as a home base station, are considered as one of the economical technologies to improve the performance of indoor users instead of macrocells. Femtocells provide coverage extension for indoor service and improve network capacity by reducing the load for macrocells. A femtocell base station (BS) is an auto-configurable and self-organizing home base station which has small service coverage (10-50 meters) as a hot-spot, which is deployed indoors or at high user density area. The physical layer technology of the femtocell BS is the same as the macrocell's, and an IP based backhaul such as the xDSL or FTTH is used to communicate with the cellular network core system [2]. The number of users who access to a femtocell BS is smaller than the number of users for a macrocell BS, and the distance between BS and users is very close. Hence the femtocell provides high speed data service easier than the macrocell.

OFDMA femtocells are developed for the next generation high speed cellular networks such as 3GPP Long Term Evolution (LTE) [3] and mobile WiMAX [4]. Generally, frequency reuse-1 system is considered as the preferred frequency reuse scheme for the OFDMA cellular network, since large reuse factor systems tend to lose more spectral efficiency by segregating bandwidth. However, reuse-1 system has the co-channel interference problem. Since femtocells are deployed in the macrocell coverage and the density of femtocells may become very high, the co-channel interference management is more critical in the femtocell networks. The co-channel interference problem is more critical in the closed access system. Typically, licensed users are allowed to access the femtocell with the closed access system. When an unlicensed user moves into the femtocell service coverage, the user has to be served not by the femtocell but by the previous femtocell or the macrocell which has served the user. In this situation, the downlink transmission of femtocell BS becomes critical interference to the unlicensed user. On the other hand, the uplink transmission of the unlicensed user causes interference to the femtocell BS. Even though the open access is applied, interference between femtocells significantly increases as the density of femtocells is grown. Therefore, interference management should be importantly considered with a proper subcarrier, bit and power allocation algorithms in OFDMA femtocell networks.

The resource management for OFDMA systems has been widely studied and many research results are presented. In terms of the purpose of the algorithms, these researches are classified into two categories, system-centric approach and application-centric approach [5]. System-centric approach is also divided into rate adaptive (RA) approaches [6][7][8][9] and margin adaptive (MA) approaches [10][11][12]. The objective of the RA method is to maximize the total data rate of the system, while the MA method concentrates on minimizing the total transmission power. In the femtocell networks, however, it is important not only to improve the performance of the overall system but also to manage co-channel interference of each subcarrier. Although the MA resource allocation approaches minimize the total

transmission power of BS, these system-centric algorithms cannot manage the transmission power of each subcarrier according to the interference condition. As a matter of fact, system-centric MA algorithms tend to allocate more resources to a subcarrier which has better channel gain without considering for the interference information.

To minimize the effect of the co-channel interference, a novel interference-aware OFDMA resource allocation algorithm is proposed in this paper. The proposed interference-aware algorithm considers the interference condition of each subcarrier in the resource allocation process, and avoids subcarriers which suffer high interference. The transmission power minimization is also performed to reduce the effect of the transmission to nearby BSs. The rest of this paper is organized as follows. Section 2 gives the system model and problem formulation for the proposed algorithm. In Section 3, we propose the interference-aware resource allocation algorithm. The performance of the algorithm is analyzed in Section 4. Finally, the paper is concluded in Section 5.

2. System Model and Problem Formulation

2.1 OFDMA Downlink System Definitions

We concentrate on the downlink resource allocation of the OFDMA system. The downlink frame of the system is partitioned in both frequency and time domain. The total available bandwidth, B is equally divided into N narrowband OFDM subcarriers, and the time domain is divided into the OFDM symbol durations. Making the bandwidth of a subcarrier suffciently smaller than the coherence bandwidth of the multipath channel, subcarriers experience flat fading on that channel [13]. A OFDM symbol duration is denoted by T_s. This research assume that intersymbol interference (ISI) resulted from multipath can be removed by using the the suitable cyclic prefix. The frequency reuse factor of the system is 1 so that all BSs use the same frequency bandwidth.

There are K users for a femtocell, and where K is significantly smaller than the number of user of a macrocell. In fact, since the femtocell BS is used for indoor communications, it is expected that the number of user for a femtocell is about up to 10 or 20. Each user has a subcarrier set, $\Omega_k(t)$ which consists of subcarriers used by user k at symbol duration t, and $\Omega(t) = \Omega_1(t) \cup \Omega_2(t) \cup \cdots \cup \Omega_K(t)$. $s_k^{(n)}(t)$ denotes the subcarrier assignment variable.

$$s_k^{(n)}(t) = \begin{cases} 1, & n \in \Omega_k(t) \\ 0, & otherwise \end{cases} \tag{1}$$

In other words, if user k uses subcarrier n at symbol duration t, $s_k^{(n)}(t) = 1$, otherwise 0. A subcarrier is not allowed to be shared by more than one user, hence

$$\sum_{k=1}^{K} s_k^{(n)}(t) = 1, \quad \forall n \tag{2}$$

Each subcarrier has a different transmission power. $p_k^{(n)}(t)$ means the transmission power allocated to user k on subcarrier n at symbol duration t, and

$$p^{(n)}(t) = \sum_{k=1}^{K} p_k^{(n)}(t), \quad \forall n \tag{3}$$

The transmission power vector is defined by $P(t) = \left\{ p^{(1)}(t), p^{(2)}(t), \cdots, p^{(N)}(t) \right\}$.

The adaptive modulation scheme is applied by selecting one of the M-QAM, where $M \in \{4, 16, 64\}$. When the amount of allocated bits for user k on subcarrier n at symbol duration t is $c_k^{(n)}(t)$, $c_k^{(n)}(t)$ can choose the value among $\{2, 4, 6\}$ where the modulation of subcarrier n is 4-QAM, 16-QAM, or 64-QAM, respectively. Selecting $c_k^{(n)}(t)$ is decided according to the channel state information (CSI) or data rate requirement. Assume that time division duplex (TDD) is applied, and the downlink CSI is estimated according to the feedback information during uplink period.

2.2 Wireless Channel and Data Rate Model

In the single cell OFDMA system, the received symbol of user k on subcarrier n at symbol duration t, $Y_k^{(n)}(t)$ is given by

$$Y_k^{(n)}(t) = h_k^{(n)}(t)X_k^{(n)}(t) + Z_k^{(n)}(t), \quad n \in \Omega_k(t) \tag{4}$$

where $X_k^{(n)}(t)$ is the transmitted symbol on subcarrier n at symbol duration t, $h_k^{(n)}(t)$ is the complex channel gain of subcarrier n for user k at symbol duration t, and $Z_k^{(n)}(t)$ is the zero mean complex Gaussian noise with unit variance. $\left|Z_k^{(n)}(t)\right|^2 = BN_0 / N$ where N_0 is the noise density. The received power of subcarrier n at symbol duration t, $\overline{p}_k^{(n)}(t)$ is

$$\overline{p}_k^{(n)}(t) = \left|h_k^{(n)}(t)\right|^2 \left|X_k^{(n)}(t)\right|^2 = \left|h_k^{(n)}(t)\right|^2 p_k^{(n)}(t) \tag{5}$$

Note that we define the received power as the power attenuated by the channel gain in order to calculate the carrier to interference plus noise ratio (CINR) easily. Basically, the radio channel model includes the distance power loss, shadowing, and multipath fading [14]. This research assumes that $h_k^{(n)}(t)$ consists of the path loss and the shadowing component. Hence, the magnitude of channel gain, $\left|h_k^{(n)}(t)\right|^2$ is expressed by

$$\left|h_k^{(n)}(t)\right|^2 = C \cdot d_k^{-\alpha} 10^{W_\sigma / 10} \tag{6}$$

where C is a constant, W_σ is the shadowing random variable, and α is the path loss exponent (PLE).

Considering multi-cell system, the received symbol of user k on subcarrier n of BS i at symbol duration t is modified as

$$Y_{i,k}^{(n)}(t) = h_{i,k}^{(n)}(t)X_{i,k}^{(n)}(t) + I_{i,k}^{(n)}(t) + Z_{i,k}^{(n)}(t), \quad n \in \Omega_k(t) \tag{7}$$

where

$$I_{i,k}^{(n)}(t) = \sum_{j \neq i} h_{j,k}^{(n)}(t)X_{j,k}^{(n)}(t) \tag{8}$$

$X_{i,k}^{(n)}(t)$ is the transmitted symbol on subcarrier n from BS i at symbol duration t, and $h_{i,k}^{(n)}(t)$ is the channel gain of subcarrier n from BS i at symbol duration t. The co-channel interference signal to subcarrier n, $I_{i,k}^{(n)}(t)$ is defined as the summation of the received signal from other BSs.

The CINR at user k on subcarrier n, $\Gamma_{i,k}^{(n)}(t)$ is given by

$$\Gamma_{i,k}^{(n)}(t) = \frac{\overline{p}_k^{(n)}(t)}{\left|I_{i,k}^{(n)}(t)\right|^2 + N_0 B / N} \tag{9}$$

The expected data rate of a subcarrier is defined by two different methods. The first method uses the Shannon capacity. Classically, the Shannon capacity has been used as the upper bound of the data rate. By the Shannon capacity, the maximum data rate of user k on subcarrier n of BS i is

$$r_{i,k}^{(n)}(t) = \frac{B}{N} \log_2 \left(1 + \Gamma_{i,k}^{(n)}(t)\right) \tag{10}$$

The total data rate of BS i is

$$R_i = \sum_{k=1}^{K} \sum_{n=1}^{N} r_{i,k}^{(n)}, \quad \forall i \tag{11}$$

The second method uses the required received power function, $f_{i,k}^{(n)}(c_{i,k}^{(n)}(t))$. This function means the minimum required received power to receive $c_{i,k}^{(n)}(t)$ bits on subcarrier n at symbol duration t, reliably. Then, the required transmission power is $f_{i,k}^{(n)}(c_{i,k}^{(n)}(t)) / \left|h_{i,k}^{(n)}(t)\right|^2$. In other words, when the required transmission power is allocated to subcarrier n, the data rate is $c_{i,k}^{(n)}(t)/T_s$ bps. In [15], one of the required received power function is defined.

$$f_{i,k}^{(n)}(c_{i,k}^{(n)}(t)) = \frac{N_0}{3} \left[Q^{-1}\left(\frac{P_e}{4}\right) \right]^2 \left(2^{c_{i,k}^{(n)}(t)} - 1\right) \tag{12}$$

where

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-t^2/2} dt \tag{13}$$

2.3 Interference-aware Optimization Problem

The interference-aware downlink resource management problem of an OFDMA femtocell BS is formulated as follows:

$$\min_{s_k^{(n)}, c_k^{(n)}} \sum_{n=1}^{N} U\left(s_k^{(n)} c_k^{(n)}\right) \tag{14}$$

subject to

$$\sum_{n=1}^{N} s_k^{(n)} c_k^{(n)} \geq T_s R_k, \quad \forall k \tag{15}$$

$$\sum_{n=1}^{N} s_k^{(n)} \leq 1, \quad \forall n \tag{16}$$

$$p_k^{(n)} \geq 0, \quad \forall k, n \tag{17}$$

$$s_k^{(n)} \in \{0, 1\}, \quad \forall k, n \tag{18}$$

$$c_k^{(n)} \in \{0, 2, 4, 6\}, \quad \forall k, n \tag{19}$$

where $U\left(s_k^{(n)} c_k^{(n)}\right)$ is the weighted transmission power of subcarrier n which transmits $c_k^{(n)}$

bits in a symbol duration, and R_k is the data rate requirement for user k. Note that the time index t and BS index i are dropped for simplicity. The weighted transmission power is defined as

$$U\left(s_k^{(n)} c_k^{(n)}\right) = \left(1 + I^{(n)}\right) \sum_{k=1}^{K} \frac{f_k^{(n)}(s_k^{(n)} c_k^{(n)})}{\left|h_k^{(n)}\right|^2}, \quad \forall n \tag{20}$$

where $I^{(n)}$ is the estimated interference for subcarrier n. Since the femtocell BS does not have any information about the interference condition of each user, BS uses the estimated interference instead of the real interference information. The estimated interference is the moving average of interference which is experienced by the femtocell BS. In order to measure the estimated interference, we assume that BS has a additional RF monitoring set. Although the amount of interference is different between the position of BS and users, the difference could be assumed to be small due to the short distance of the femtocell BS and users. Hence the estimated interference for subcarrier n of BS i is defined by

$$I^{(n)} = \frac{1}{T} \sum_{t=\tau-T-1}^{\tau-1} \left(\sum_{j \neq i} \left|h_{j,i}^{(n)}(t)\right|^2 \sum_{k=1}^{K} p_{j,k}^{(n)}(t) \right), \quad \forall n \tag{21}$$

where $h_{j,i}^{(n)}(t)$ is the channel gain of subcarrier n from interfering BS j to BS i, $p_{j,i}^{(n)}(t)$ is the transmission power of subcarrier n of BS j to its user k, T is the observation period, and τ is the current symbol duration. The estimated interference is able to be replaced by the real interference term with the interference feedback system.

The weighted transmission power means the transmission power of subcarrier n weighted by the estimated interference. The first term from the development of equation (20) is the typical transmission power of subcarrier n, and the second term denotes the amount of weight which is proportional to interference. Therefore, a subcarrier which suffers more interference has larger weighted transmission power than other subcarriers, although the allocated transmission power is equal. If a subcarrier has no interference, the weighted transmission power of the subcarrier is the same as the typical transmission power. Finally, the objective function minimizes the total weighted transmission power of femtocell BS, so that the subcarrier which suffers more interference has less transmission power and bits.

Constraint (15) satisfies the data rate requirement of each user. The left hand side of the constraint means the total transmitted bits to user k in a symbol duration, hence the amount of these bits should be greater than or equal to the required transmitted bits of user k, $T_s R_k$. Constraint (16) allows that a subcarrier is allocated to only one user during symbol duration, and Constraint (17) means that the transmission power should be positive or zero.

The problem formulated by (14)-(19) is a mixed integer nonlinear programming (MINLP) problem. The objective function (14) is not convex and linear, and the number of integer optimization variables is $2KN$. It has K nonlinear constraints (15) and $(1+K)N$ linear constraints (16)-(17). Therefore, the global optimization solution will not be guaranteed for this problem generally.

To solve the problem more simply, we use a problem converting method which is introduced in [11]. This method linearizes and simplifies the MINLP problem into an equivalent binary linear programming (BLP) problem without any loss of optimality.

The objective function (14) can be rewritten as

$$\sum_{n=1}^{N} \alpha \left(1 + I^{(n)}\right) \sum_{k=1}^{K} \frac{2^{s_k^{(n)} c_k^{(n)}} - 1}{\left|h_k^{(n)}\right|^2}, \quad \forall n \tag{22}$$

where

$$\alpha = \frac{N_o B}{3N} \left[Q^{-1} \left(\frac{P_e}{4} \right) \right]^2 \tag{23}$$

Since $s_k^{(n)} c_k^{(n)} \in \{0, 2, 4, 6\}$, $2^{s_k^{(n)} c_k^{(n)}} - 1$ only takes a value from $\{0, 3, 15, 63\}$. Therefore, (22) can be replaced by

$$\sum_{n=1}^{N} \alpha \left(1 + I^{(n)}\right) \sum_{k=1}^{K} \frac{3 \left(x_{1,k}^{(n)} + 5 x_{2,k}^{(n)} + 21 x_{3,k}^{(n)}\right)}{\left|h_k^{(n)}\right|^2}, \quad \forall n \tag{24}$$

with additional constraints for $x_{u,k}^{(n)}$:

$$0 \le \sum_{u=1}^{3} x_{u,k}^{(n)} \le 1, \quad \forall k, n \tag{25}$$

$$x_{u,k}^{(n)} \in \{0, 1\}, \quad \forall k, n, u \tag{26}$$

where $u \in \{1, 2, 3\}$. These constraints ensure that all $x_{u,k}^{(n)}$ should be zero or only one of $x_{u,k}^{(n)}$ can be 1. Using the definition of $x_{u,k}^{(n)}$, $s_k^{(n)} c_k^{(n)}$ can be replaced by

$$s_k^{(n)} c_k^{(n)} = \sum_{u=1}^{3} 2u \cdot x_{u,k}^{(n)}, \quad \forall k, n \tag{27}$$

This replacement converts nonlinear constraints (15) to linear constraints.

The converted BLP problem is as follows:

$$\min_{x_{u,k}^{(n)}} \sum_{n=1}^{N} \alpha \left(1 + I^{(n)}\right) \sum_{k=1}^{K} \frac{3 \left(x_{1,k}^{(n)} + 5 x_{2,k}^{(n)} + 21 x_{3,k}^{(n)}\right)}{\left|h_k^{(n)}\right|^2} \tag{28}$$

subject to

$$\sum_{n=1}^{N} \sum_{u=1}^{3} 2u \cdot x_{u,k}^{(n)} \ge T_s R_k, \quad \forall k, \tag{29}$$

$$0 \le \sum_{u=1}^{3} x_{u,k}^{(n)} \le 1, \quad \forall k, n \tag{30}$$

$$x_{u,k}^{(n)} \in \{0, 1\}, \quad \forall k, n, u \tag{31}$$

When $s_k^{(n)} = 0$ or 1, $\sum_{u=1}^{3} x_{u,k}^{(n)}$ becomes 0 or 1. Thus constraints (30) can replace (16).

Consequently, the number of optimization variables increases to $3KN$, however the computational complexity of the BLP problem is much smaller than the original MINLP problem. The solution of the BLP problem is obtained by the simplex method [16].

3. Interference-Aware Resource Allocation Algorithm

Although the aforementioned numerical solution shows how to decide the resource allocation by the theoretical way, this solution has a difficulty of implementation in practical systems. The BLP method solves the problem by using linear programming, thus the complexity is reduced and the solution is clear. However, it is still difficult to solve the BLP problem by the simplex method with the large number of optimization variables, since the time period to decide resource allocation is very short in practical systems. Generally, the simplex method has exponential time complexity in the worst case [17]. Therefore, this section proposes a heuristic algorithm to solve the problem with low complexity.

3.1 Function Definitions

This section defines functions which are used in the heuristic algorithm.

sort(A)
This function returns the order matrix $O = \left\{ o_k^{(n)} \right\}$ of the matrix A. A is a K by N matrix. $o_k^{(n)}$ denotes the order of $a_k^{(n)}$ among $\left\{ a_k^{(1)}, a_k^{(2)}, \cdots, a_k^{(N)} \right\}$.

$$
\begin{pmatrix} o_1^{(1)} & \cdots & o_1^{(N)} \\ \vdots & \ddots & \vdots \\ o_K^{(1)} & \cdots & o_K^{(N)} \end{pmatrix} = \mathrm{sort} \begin{pmatrix} a_1^{(1)} & \cdots & a_1^{(N)} \\ \vdots & \ddots & \vdots \\ a_K^{(1)} & \cdots & a_K^{(N)} \end{pmatrix} \tag{32}
$$

argmin(A)
Returning 1 by N matrix M of this function denotes the index for the minimum value of each column of A. In ohter words, $m^{(n)}$ is the index of the minimum value among $\left\{ a_1^{(n)}, a_2^{(n)}, \cdots, a_K^{(n)} \right\}$.

$$
\begin{pmatrix} m^{(1)} & \cdots & m^{(N)} \end{pmatrix} = \mathrm{argmin} \begin{pmatrix} a_1^{(1)} & \cdots & a_1^{(N)} \\ \vdots & \ddots & \vdots \\ a_K^{(1)} & \cdots & a_K^{(N)} \end{pmatrix} \tag{33}
$$

3.2 Resource Allocation Algorithm

The resource allocation algorithm of the heuristic solution is performed by following procedure.

Initialization

Initialize the subcarrier set $\Omega_k = \phi$ and the subcarrier candidate set $\Omega_{k,candi} = \phi$, $\forall k$.

Let U be the weighted transmission power matrix, and the elements of U is calculated by equation (20).

$$
U = \begin{pmatrix} U(s_1^{(1)} c_1^{(1)}) & \cdots & U(s_1^{(N)} c_1^{(N)}) \\ \vdots & \ddots & \vdots \\ U(s_K^{(1)} c_K^{(1)}) & \cdots & U(s_K^{(N)} c_K^{(N)}) \end{pmatrix} \tag{34}
$$

Required transmission power

P	Subcarrier				
	1	2	3	4	5
User 1	3	2	3	1	1
2	1	8	7	10	8

$T_sR_1=4$
$T_sR_2=8$

Greedy algorithm

S	1	2	3	4	5
1	0	1	1	1	1
2	1	0	0	0	0

C	1	2	3	4	5
1	0	0	0	2	2
2	6	0	0	0	0

Proposed algorithm

U	1	2	3	4	5
1	4	3	6	2	7
2	2	9	8	13	11

O	1	2	3	4	5
1	3	2	4	1	5
2	1	3	2	5	4

S	1	2	3	4	5
1	0	1	0	1	0
2	1	0	1	0	1

C	1	2	3	4	5
1	0	2	0	2	0
2	4	0	2	0	2

Fig. 1. Algorithm examples

and if user k has no data to transmit,

$$U(s_k^{(n)}c_k^{(n)}) = \infty, \ \forall n \tag{35}$$

The order matrix O is derived by

$$O = \text{sort}(U) \tag{36}$$

$o_k^{(n)}$ means that the weighted transmission power of subcarrier n for user k is the $o_k^{(n)}$ th smallest among all the subcarriers.

Subcarrier selection

This process decides the subcarrier candidate set, $\Omega_{k,candi}$.

$$M = \text{argmin}(O) \tag{37}$$

and

$$\Omega_{k,candi} = \left\{ n \mid m^{(n)} = k \right\} \tag{38}$$

Bit and power allocation

For each user,

$$n' = \text{argmin}\,(U_k) \tag{39}$$

where U_k consists of the elements for subcarriers in $\Omega_{k,candi}$ from the kth raw vector of U. If $T_s R_k$ is positive,

$$c_k^{(n')} = 2 \tag{40}$$

$$\Omega_k = \Omega_k \cup n' \tag{41}$$

$$\Omega_{k,candi} = \Omega_{k,candi} - n' \tag{42}$$

$$T_s R_k = T_s R_k - 2 \tag{43}$$

This process is performed iteratively until $\Omega_{k,candi} = \phi$ or $T_s R_k = 0$. If $\Omega_{k,candi} = \phi$ and $T_s R_k \neq 0$, set $\Omega_{k,candi} = \Omega_k$ and perform this process again until $T_s R_k = 0$.

   Fig. 1 presents an example of the proposed heuristic algorithm compared with the typical greedy resource allocation algorithm, when two users share five subcarriers. The bit requirements of users are 4 and 8 respectively. *P* denotes the required transmission power with 2 bits for each subcarrier. Generally, subcarriers with good channel gain have smaller transmission power. The greedy algorithm allocates a subcarrier to the user who has the smallest value of the required transmission power for the subcarrier. *S* shows the subcarrier allocation status, and *C* is the actual bit allocation. The greedy algorithm allocates bits to subcarriers by order of the required transmission power. Consequently, the user with good channel gain tends to occupy almost all of subcarriers. According to *C*, user 2 has only one subcarrier and the bit requirement is not satisfied. While the proposed algorithm uses a relative order of the weighted transmission power. *O* means the relative order of subcarriers in terms of weighted transmission power for each user. Choosing users by this order matrix, the subcarrier allocation is fairer than the greedy algorithm. Moreover, the proposed algorithm allocates according to the weighted transmission power, hence the interference avoidance performance is better than the greedy algorithm, although more transmission power is used. As a matter of fact, the total transmission power of each algorithm is 3 and 19, however the total amount of the interference which is experienced by users is 9 and 7 respectively.

4. Numerical Results

The Monte Carlo method is applied to evaluate the performance of the proposed algorithm. **Table 1** presents the system parameters for the simulation. The femtocells are uniformly deployed in the area with radius of 100 m, and the radius of the service coverage of a femtocell is 30 m. Each femtocell has three users, and the positions of users are randomly selected in the
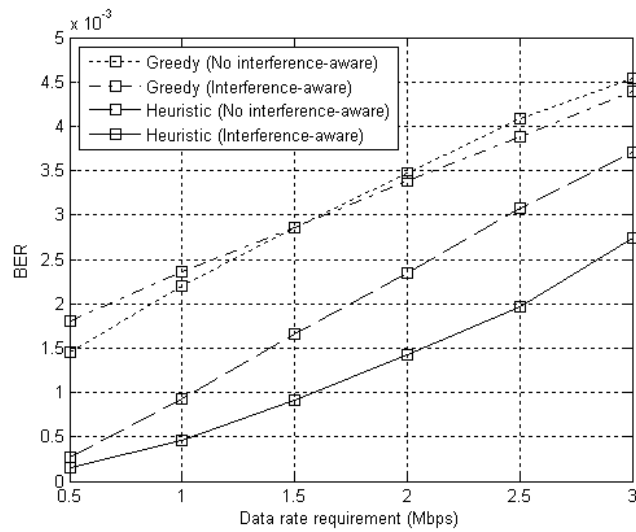
Table 1. Simulation parameters

Parameter	Value
Topology radius	100m
Femtocell radius	30 m
Number of users per femtocell	3
Total system bandwidth	2.5 MHz
Number of subcarriers	256
Symbol duration	100 μ s
Path loss exponent	3

Standard deviation of lognormal fading	5 dB
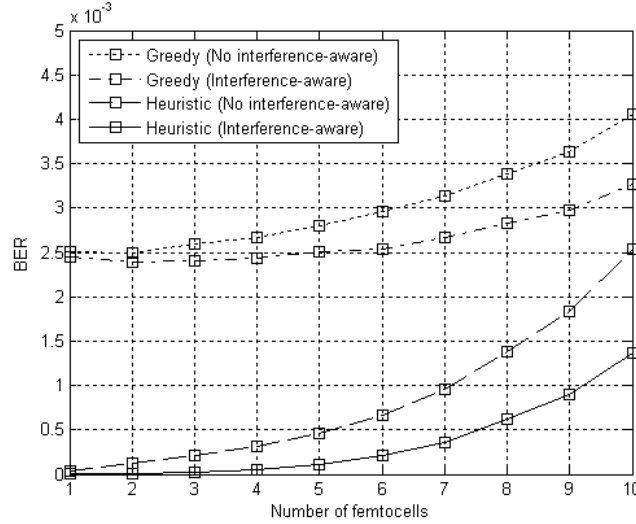
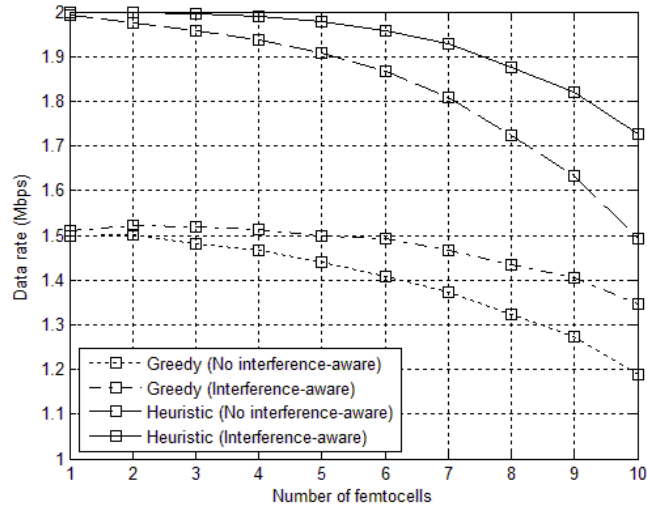**(a)** Data rate requirment: 2 Mbps
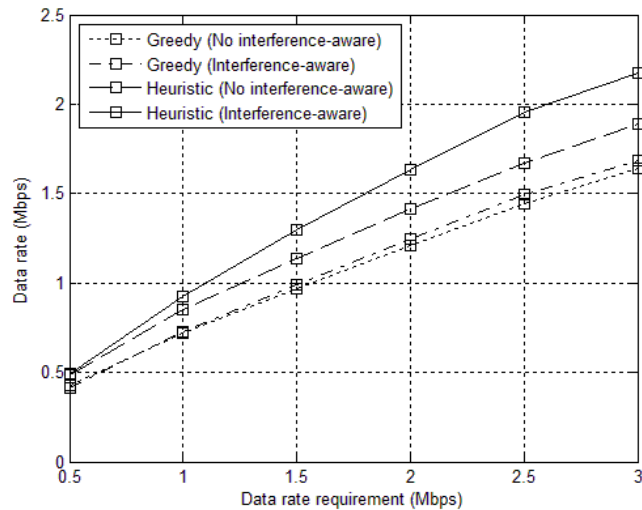

(b) Number of femtocell: 10

Fig. 2. Bit error rate in terms of the number of femtocells **(a)** and the data rate requirement **(b)**

service coverage of respective femtocell at each simulation. Assume that all users are mutually independent from each other, and the mobility of user is not considered.

The algorithms to be compared are the greedy algorithm with and without interference-aware allocation, and the heuristic algorithm with and without interference-aware allocation. The algorithms without interference-aware allocation mean that objective function for the resource allocation does not consider the effect of interference, while the interference-aware algorithms use equation (14) as the objective function. In other words, the greedy algorithm without interference-aware allocation applies greedy allocation method to P, the greedy algorithm with interference-aware allocation applies greedy allocation method to U, the heuristic algorithm without interference-aware allocation uses $O = \text{sort}(P)$ instead
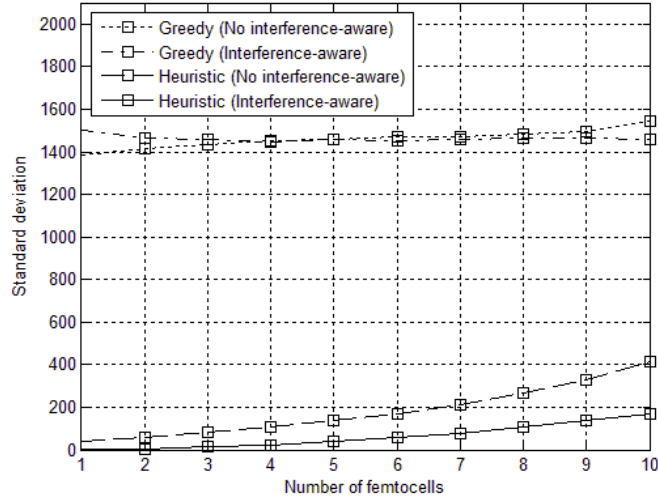
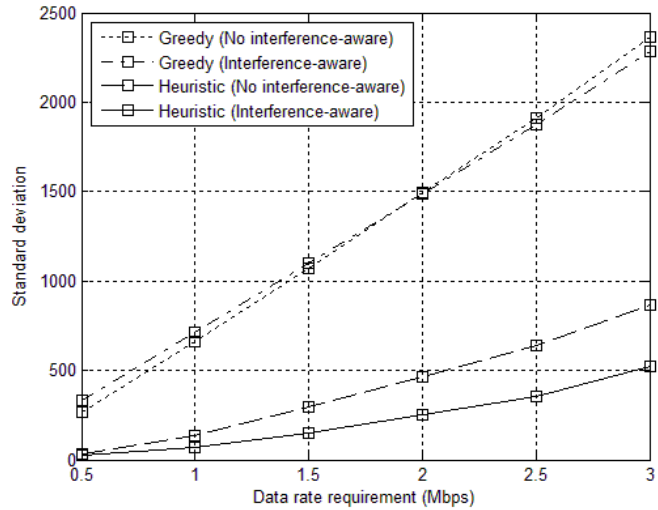**(a)** Data rate requirment: 2 Mbps

(b) Number of femtocell: 10

Fig. 3. Average data rate in terms of the number of femtocells **(a)** and the data rate requirement **(b)**

of (36). Therefore, the heuristic algorithm with interference-aware allocation is our complete resource allocation algorithm.

Fig. 2 shows the average BER performance of the algorithms. The average BER is a typical factor which represents the effect of co-channel interference. Generally, high density of femtocells causes more co-channel interference, thus the average BER increases. Since the greedy algorithm allocates almost of subcarriers to the user with good channel state, other users use a few subcarriers, and the performance of these users is very poor. Hence the average BER of users becomes very high in spites of the good performance of the best user. A user with small number of subcarriers allocates more transmission power to a subcarrier than the user with large number of subcarriers, and more transmission power causes more interference. Although the interference-aware allocation method is helpful to reduce the average BER, it is

(a) Data rate requirment: 2 Mbps

(b) Number of femtocell: 10

Fig. 4. Standard deviation of data rate in terms of the number of femtocells (a)
and the data rate requirement (b)

still higher than the performance of the heuristic algorithm. The heuristic algorithm fairly allocates subcarriers to each user, and efficiently avoids the co-channel interference. Therefore, the average BER of the proposed algorithm is maintained low with the high density of femtocells.

The data rate performance shows that the heuristic algorithm guarantees the fairness among users. Fig. 3 presents the average data rate of users in terms of the number of femtocells and the data rate requirement of user. The greedy algorithm cannot satisfy the user requirement even in the low density femtocell network, since a good user has too many subcarriers more than necessary, while other users have insufficient subcarriers to satisfy the data rate requirement. The heuristic algorithm guarantees the fair subcarrier allocation between users,

and the waste of subcarriers is prevented. The gap of the average data rate between the greedy algorithm and the heuristic algorithm becomes large with the high data rate requirement. The standard deviation of data rate presented in **Fig. 4** shows the user fairness of the algorithm more clearly. The standard deviation is the parameter which expresses the difference of data rate among users. As a metter of fact, user data rate of the greedy algorithm has higher standard deviation than the data rate of the heuristic algorithm.

According to the simulation results, the proposed interference-aware resource allocation algorithm has better performance to optimize subcarrier allocation and avoid co-channel interference than the traditional greedy algorithm.

5. Conclusions

An interference-aware resource allocation algorithm for the downlink of OFDMA femtocell networks is proposed in this paper. The proposed algorithm applies a novel objective function to optimize OFDMA resource allocation, and a heuristic algorithm is introduced to solve the problem. The effect of co-channel interference is considered in the objective function, and the heuristic algorithm guarantees user fairness and reduce the computational complexity. The simulation results show that the performance of the proposed algorithm is better than the traditional greedy resource allocation algorithm. However, the algorithm only considers the PHY layer, and cannot reflect the real packet traffic situation in MAC layer. In fact, the packet-level QoS is more critical to the service than the bit-level QoS. Therefore, the next research works include a cross-layer solution to consider the traffic behavior in MAC layer packet queues.

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