Game Based Self-Organizing Scheme for Femtocell Networks

Kwanghun Han[1], Seunghyun Choi[1], Du Ho Kang[2], and Sunghyun Choi[1]

[1] School of Electrical Engineering and INMC, Seoul National University, Korea
[2] Wireless@KTH, Royal Institute of Technology (KTH), Sweden
{khhan,shchoi}@mwnl.snu.ac.kr, schoi@snu.ac.kr

Abstract. A femto base station (BS) is an emerging candidate solution to guarantee wireless coverage and enhance capacity in indoor environments. Ideally, femto BSs should be designed to be installed by customers without their manual configuration. Hence, a femtocell network should be automatically organized by configuring the operating frequency channel and transmit power level of the femto BSs adaptively according to the interference environment. However, in order to enhance the capacity of femtocell users, the femto BSs in the network should be carefully configured since they can cause severe co-channel interference to the existing macrocell networks operating in the same frequency channel. In this work, we propose an automatic self-organizing scheme for a femtocell network by jointly considering transmit power control and dynamic frequency selection, which tries to maximize the mean sum downlink achievable rate of the femtocell users and to guarantee the performance of the macrocell users by limiting the co-channel interference from the femtocells. The proposed scheme is based on a potential game which guarantees a convergence property, and we enhance the scheme with a Tabu search, which attempts to achieve the optimality.

1 Introduction

As the demand of data traffic rapidly increases, securing wireless coverage and enhancing capacity in an indoor environment, where a big portion of wireless data service occurs, become more important. Conventionally, installing radio frequency (RF) repeaters is a widely adopted solution for it since it is simple and cheap. However, a repeater cannot fundamentally increase the wireless capacity since it simply amplifies and repeats the signal from the macro base station (BS). A small BS, which is commonly referred to as a femto BS, is a more attractive solution compared with the repeater since a femto BS can achieve a higher wireless capacity by achieving better spectral efficiency [1]. A femto BS is a small low-cost BS serving a small area referred to as a femtocell [2]. A femto BS is usually connected to a macrocell network via a broadband wired connection, e.g., an Internet protocol (IP) network over x digital subscriber line (xDSL) or a dedicated backhaul network. The emerging IMT-advanced candidate systems including 3GPP LTE-advanced and IEEE 802.16m also feature this femtocell technology [3, 4, 5].

R. Jain and R. Kannan (Eds.): GameNets 2011, LNICST 75, pp. 57–75, 2012.

Considering a large number of expected femto BS deployments, the desirable features of femto BSs include 1) minimizing the cost of installation and maintenance of a femto BS and 2) operating the femto BS without any in-depth knowledge of the network. Due to such features, self-organizing network (SON) is considered an indispensable technique for the success of femtocell networks, where SON is defined as a network which can be autonomously organized with a minimum intervention of the network operator/user. In a self-organizing femtocell network, each BS becomes self-organized by adaptively adjusting its transmit power and operating frequency channel.

For the femtocell network, in [6], the authors propose a heuristic algorithm for selecting the frequency band. The effect of network parameters, e.g., transmit power of femto BS, femtocell radius, and loading factor, are evaluated. Moreover, they propose an heuristic dynamic frequency selection (DFS) algorithm of the IEEE 802.16e femtocell systems in terms of the network coverage and the system capacity. In [7], the deployment of femto BSs is discussed for an intelligent cell planning. The authors propose a frequency assignment technique considering the distance to the macro BS. The main issue of this paper is to determine the distance threshold for the frequency channel assignment. In addition, transmit power control (TPC) for femtocell networks is investigated in [8, 9, 10, 11]. However, most of the papers assume the uplink transmission since it is easy to quantify and limit the sum interference to the macro BS. Moreover, the optimization goal of TPC is not to maximize the sum capacity of the network but to guarantee the target SINR, since such an objective is easy to solve, while the capacity maximization is more appropriate for the data network.

We in this work consider the joint problem of DFS and TPC as the goal of SON, and develop an operational procedure for a practical application of SON, which is referred to as a SON operation. For the algorithm, we consider the downlink system, which is different from the uplink system in that the victims of the co-channel interference are the macrocell users and femtocell users. The problem in consideration tries to maximize the mean sum downlink achievable rate of the femtocell users while guaranteeing the performance of the macrocell users by limiting the co-channel interference from femtocells. We develop an algorithm for a SON operation based on a potential game, which systematically has a strong convergence property. Even though the proposed algorithm cannot be fully distributed since it requires the network-wide information, the operation can be distributed with a proper initialization procedure. In addition, since the considered problem is known as NP-hard and the proposed algorithm does not guarantee optimality, the proposed algorithm might not result in an optimal solution. Consequently, the game algorithm is enhanced by applying a Tabu search, which attempts to obtain the optimal value, and we evaluate the proposed algorithm via simulations. To our best knowledge, the network-wide optimality is desirable but has not been handled so far since it is difficult to be modeled and achieved.

The rest of this paper is organized as follows. In Section 2, we describe a joint DFS/TPC problem in a self-organizing femtocell network, and then a system model is represented in Section 3. A potential game based SON algorithm is presented in

Section 4, and the detailed operation of the proposed scheme is explained in Section 5. In Section 6, the Tabu game algorithm is proposed, and we evaluate the proposed algorithm in Section 7. Finally, we conclude the paper in Section 8.

2 Self-Organizing Femtocell Network

Assume that femto BSs are arbitrarily distributed across the area in consideration, and each femto BS attempts to maximize the communication rate with its associated users. If multiple channels are available, the femto BSs prefer to utilize a frequency channel which is orthogonal to other femto BSs' since it is the simplest solution for the rate maximization. However, as the number of femto BSs increases more than the number of available frequency channels, femto BSs might inevitably interfere with each other. As a result, each femto BS should mitigate co-channel interference by controlling its transmit power (i.e., TPC) as well as changing its operating frequency channel (i.e., DFS) according to the interference environment. Moreover, considering the expected huge number of femto BSs, it is almost impossible to keep the network optimized via the manual setting by a human engineer as done in conventional cellular networks. Therefore, the femtocell network is desired to be a SON.

Developing a SON operation which tries to maximize the sum throughput of femtocells is challenging in that co-channel interference severely affects the sum throughput of femtocells. It is beacuse the signal-to-interference and noise ratio (SINR) of a femto BS is in proportion to the desired signal's power increment whereas it is inversely proportional to the transmit power increment of other BSs in the same frequency channel. Therefore, mitigating such co-channel interference is the key issue of the SON operation.

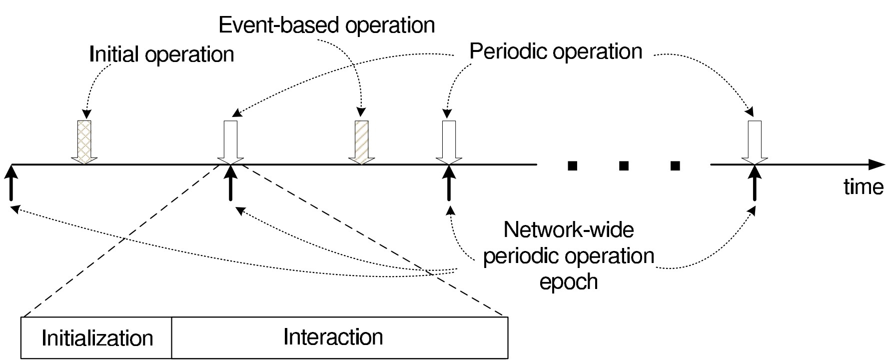


Fig. 1. The SON operation of a femto BS is depicted. For a periodic operation, the network determines the operation epoch, and the femto BSs conduct the SON operation. Such a periodic operation is the most essential and important SON operation for the network management. In addition, the initial and event-based SON operations are also considered. In this work, the SON operation is assumed to be composed of two procedures, i.e., the initial and interaction procedures.

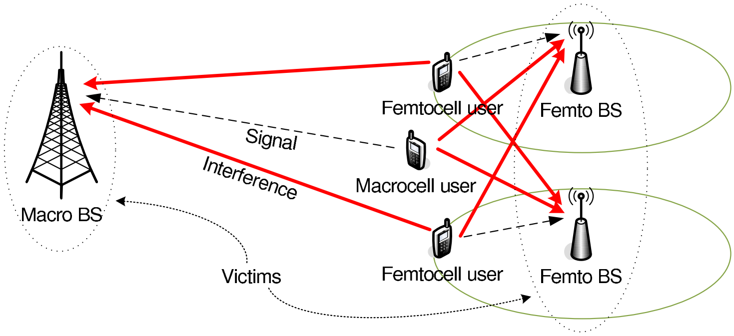


Fig. 2. During the uplink transmission, the macrocell and femtocell users transmit the data to the serving BSs. Since the receivers are the BSs, the victims by the interferences are also the BSs.

In this work, we mainly concentrate on the problem with a network-wide objective function, i.e., the mean sum downlink achievable rate of the femtocell network while maintaining the SINR of the macrocell users, represented as follows:

$$\max \quad \sum_{i \in U_f} R_i \tag{1}$$

$$\text{s.t.} \quad \eta_j > \eta_{th} \qquad \forall j \in U_m \tag{2}$$

where R_i is the mean downlink achievable rate of femtocell user i and U_f is the index set of the femtocell users. η_j is the downlink SINR of macrocell user j and U_m is the index set of the macrocell users. η_{th} is the SINR threshold for guaranteeing the performance of the macrocell users. The problem modeling and formulation is presented in Section 3.

Lastly, we need to define the period of the SON operations. Practically, the SON operation does not need to be realtime, since the SON operation is not a part of resource scheduling but a part of network configuration. In Fig. 1, three types of operations are depicted. First, a femtocell network conducts the SON operation periodically in order to maintain the change of the network as time passes. During the periodic SON operation, each femto BS can reflect the SINR constraints of the macrocell users. The period of this operation might be enough to be done once a day or several days, for instance. Second, an initial SON operation is conducted for the initial setup of a femto BS which is newly added. When the initial operation is conducted, the femto BS might lack necessary information, e.g., channel information among other femto BSs and the SINR constraints of neighboring macrocell users. Then, it is hard to optimize the SON parameters. Third, the SON operation could be initiated based on the event of the network changes, e.g., neighboring femto BS addition and removal.

3 Modeling of Femtocell Network

In this work, we consider the downlink of a femtocell network and try to solve the problem which tries to maximize the sum rate of femto users while considering the constraints of the macrocell user's interference. In the femtocell network, the co-channel interference problems of downlink and uplink are different. As shown in Figs. 2 and 3, the main difference is that victims of the interference are different. For the uplink transmission, the victims of the interference are the BSs, i.e., macro BSs and femto BSs. Since the victims are static, the uplink problem is relatively easy to measure the interference level. Especially, the interference level of the macrocell can be measured only at the macro BS, and it is possible to limit the interference level under the interference threshold easily. Whereas, for the downlink transmission, the victims are the macrocell and femtocell users. Therefore, it is complicated to measure and limit the interference level since the users are ephemeral, distributed and even mobile, and we need to clearly analyze the victims to solve the problem and apply the solution to the practical system.

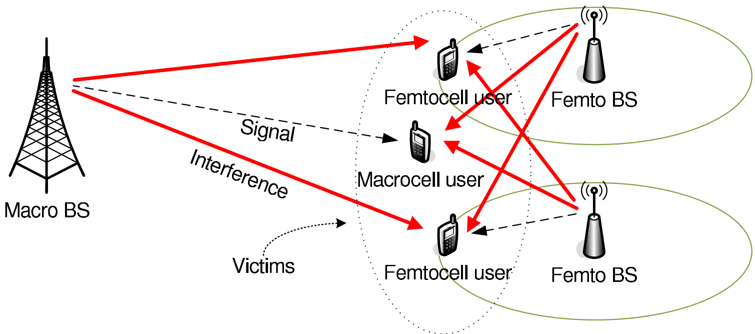


Fig. 3. During the downlink transmission, the macro and femto BSs transmit the data to the associated users. Since the receiver are the users, the victims by the interferences are also the users.

In Fig. 4, the downlink system model in consideration is depicted. In order to measure the performance of a femtocell, we consider the mean downlink achievable rate of an arbitrary user in the cell, $\tilde{R}$. As shown in the figure, a user is assumed to be located at the the arbitrary distance of r_u from the femto BS. Then, the achievable rate, $R_i(f_i, p_i)$, of femto BS i operating with transmit power of p_i in frequency channel f_i can be represented and calculated from the SINR of femtocell user j, $\gamma_j(f_i, p_i)$:

$$I(f_i) := \sum_{k \in B_m(f_i)} I_k(l_j) + \sum_{k \in B_f(f_i), k \neq i} I_k(l_j), \tag{3}$$

$$\gamma_j(f_i, p_i) = \frac{g_{ij} p_i}{N_0 + I(f_i)}, \tag{4}$$

$$R_i(f_i, p_i) = B \log\left(1 + \gamma_j(f_i, p_i)\right) \tag{5}$$

where the g_{ij} is the channel gain between the femto BS i and user j, and p_i is the transmit power of femto BS i. N_0 is the noise power, and $I_k(l_j)$ is the interference from macro or other femto BS k which is experienced by user j located at l_j.

$B_m(f_i)$ and $B_f(f_i)$ are the index sets of macro BSs and femto BSs, operating in frequency channel f_i, respectively. B is the bandwidth of the considered system.

Note that the interference needs to be averaged to get the mean downlink achievable rate, $\tilde{R}_i(f_i, p_i)$. Then, we average the interference for all the users at the arbitrary distance of r_u from the femto BS:

$$\tilde{I}(f_i) := \sum_{k \in B_m(f_i)} \frac{\int_C I_k(l_j) dl_j}{2\pi r_u} + \sum_{k \in B_f(f_i), k \neq i} \frac{\int_C I_k(l_j) dl_j}{2\pi r_u} \tag{6}$$

where $\int_C I_k(l_j) dl_j$ is the line integral of function $I_k(l_j)$ along a piecewise smooth curve C, and C in this work is a circle with radius r_u centered at femto BS i. We assume that arbitrary users are continuously located at point l_j on C.

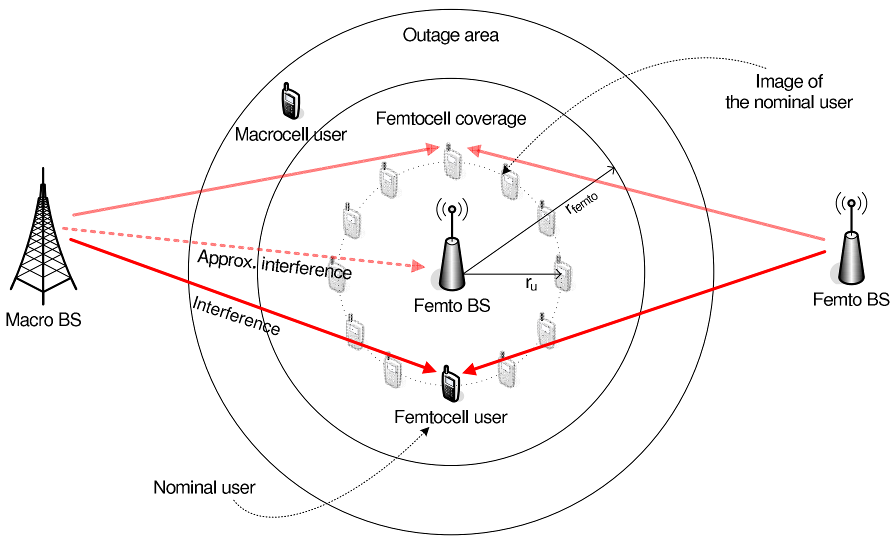


Fig. 4. The system model in consideration is depicted. To model the downlink performance of a femtocell, we use the mean downlink achievable rate of an arbitrary femtocell user located at a given distance. In addition, the macrocell users are considered to represent the interference to the macrocell.

For the simplicity, we approximate the mean interference as follows:

$$\tilde{I}(f_i) \approx \sum_{k \in B_m(f_i)} I_k(L_j) + \sum_{k \in B_f(f_i), k \neq i} I_k(L_j) \tag{7}$$

$$= \sum_{k \in B_m(f_i)} g_{ki} P + \sum_{k \in B_f(f_i), k \neq i} g_{ki} p_k \tag{8}$$

where L_j is the location of femtocell user j colocated with femto BS i, and P and p_k are the transmit power of a macro BS and femto BS k, respectively. g_{ki} is the channel gain between BSs k and i. We assume that the average amount of the interference of all the femtocell users at the arbitrary distance of r_u is the same as the amount of the interference to femtocell user j located at L_j. Note that the exact calculation of the average interference might be insignificant as long as the calculation method is identical to all the femto BSs. Consequently, the approximated mean SINR is represented as follows:

$$\widetilde{\gamma}_j(f_i, p_i) := \frac{g_{ij}p_i}{N_0 + \tilde{I}(f_i)} \tag{9}$$

where the g is identical since the distance from the serving femto BS to users is identical. Consequently, the mean downlink achievable rate of femto BS i is as follows:

$$\tilde{R}_i(f_i, p_i) := B \log_2 (1 + \widetilde{\gamma}_j(f_i, p_i)). \tag{10}$$

Even though the throughput might be more proper metric to represent the performance of a cell, the throughput is tightly related with scheduling algorithms and the user distribution. Then, it is not easy to calculate the throughput without considering a specific resource scheduler, and we will leave it as a future work. Instead, we use the achievable rate as a performance metric in this work.

As a main constraint, we need to limit the interference amount from the femto BSs to the macrocell users. In Fig. 4, the outage area is depicted, and the macrocell users in this area need to be considered as monitoring users. The interference level of the monitoring users needs to be limited under the threshold to guarantee the performance of the macrocell users. Then, we consider the feedback based reporting procedure of the monitoring users, and it will be detailed in Section 5.

4 Potential Game for SON Operation

The centralized optimization problem which maximizes the sum downlink rate of femtocell users requires high computational power and is not able if there is no central decision entity [12]. Thus, an efficient algorithm with distributed decision entities is more desirable even at the cost of optimality. In this section, we model the interaction among femto BSs as a constrained potential game which guarantees the convergence.

Game is a branch of applied mathematics, which describes and analyzes the problem of strategic interactions among multiple players who attempt to maximize their utility. Essentially, a game consists of 1) two or more players which interact one another, 2) utility functions which each player wants to maximize or minimize, and 3) action space from which players select their strategies. Then, a normal form game is represented as follows:

$$\Gamma = < N, A_i, u_i > \tag{11}$$

where $N = 1, 2, ..., |N|$, is a set of players of the game. A_i and u_i denote the action set and the utility function of player i, respectively. The action space of all available actions for all players is represented by $A = \times_{i \in N} A_i$, and $u_i : A \rightarrow \Re$,

Algorithm 1. Game Algorithm with Constraints

Initialization, $\forall i \in B_f$

$act_i \leftarrow (RND(f), RND(p))\,,\ act_i \in \mathbb{F} \times \mathbb{P}$
$titr_i \leftarrow 0,\ citr_i \leftarrow 0,\ cutil_i \leftarrow 0$

Iteration, $\forall i \in B_f$

while $titr_i < titr_{th}$ **and** $citr_i < citr_{th}$ **do**
  $titr_i \leftarrow titr_i + 1, butil_i \leftarrow 0, bact_i = (0,0), cret_i \leftarrow 0$
  Gets the current network state: $cst_i \leftarrow (\mathbf{f}_{-i}, \mathbf{p}_{-i})$
  Waiting for a decision epoch
  if $DEC(|B_f|) \neq$ success **then**
    continue
  else
    for $tact_i \leftarrow (f,p),\ \forall (f,p) \in \mathbb{F} \times \mathbb{P}$ **do**
      if $CONST(tact_i, cst_i) = 1$ **then**
        continue
      if $CONST(tact_i, cst_i) = 0$ **and** $cret_i = 0$ **then**
        $cret_i \leftarrow 1$
      if $UTIL(tact_i, cst_i) > butil_i$ **then**
        $butil_i \leftarrow UTIL(tact_i, cst_i),\ bact_i \leftarrow tact_i$
    if $cret_i = 0$ **then**
      $act_i \leftarrow (RND(f), RND(p))\,,\ act_i \in \mathbb{F} \times \mathbb{P}$
      continue
    if $cutil_i < butil_i$ **then**
      $citr_i \leftarrow 0, cutil_i \leftarrow butil_i,\ cact_i \leftarrow bact_i$
    else
      $citr_i \leftarrow citr_i + 1$
    $act_i \leftarrow bact_i$

where $\times$ means Cartesian product and $\Re$ is the set of real values. At each decision epoch of a game referred to as a stage, the players who are involved in a game attempt to maximize or minimize their utilities according to decision and order. In this work, we consider a best response policy as a decision rule. At each stage, player i determines an action $b_i \in A_i$ such that $u_i(b_i, a_{-i}) > u_i(a_i, a_{-i})$, while other players continue to implement the same actions. Here, $a_i \in A_i$ is an action of player i, and $a_{-i} \in \underset{j \neq i, j \in N}{\times A_j}$ is an action vector of all the players except player i. In addition, we assume that the order of decision is randomly determined before the game converges.

When a normal form game is conducted repeatedly, players determine actions that improve their utility functions at each stage. As the players adapt their actions, the game might reach a certain point where no players can increase their utilities without changing other players' actions. This point is called a Nash equilibrium, which is an action profile from which no player can improve its utility value by unilateral deviations, and an actual convergence point of a game. An action profile $a \in A$ is a NE if and only if $u_i(a) \geq u_i(b_i, a_{-i})\ \forall i \in N, a \in A, b_i \in A_i, a_{-i} \in \underset{j \neq i, j \in N}{\times A_j}$. However, it should be noted that a Nash equilibrium does not guarantee a point which maximizes the sum capacity of all players. Even worse, in general, a game does not always converge to a Nash equilibrium.

Fortunately, a special type of game, called potential game, is proven to converge to a Nash equilibrium [13]. A potential game is a normal form game such that any changes in the utility function of any player in the game due to a unilateral deviation by the player is reflected in a potential function. In other words, a player's individual choice increasing its own utility increases the whole network utility. Potential games with finite number of players and finite action space have been proved to converge to a Nash equilibrium when they follow a best (or better) response policy, and we also have an additional flexibility of the decision order [13]. In detail, at each decision epoch, the number of players can be more than one, and it is more desirable for the distributed operation.[1]

To resolve the convergence issue for the distributed decision structure, we can model the problem as a potential game. In our game, the femto BSs are regarded as players, and action space consists of discrete level of powers and frequency channels. Every femto BS i, which is a player, takes actions, i.e., changes its operating frequency channel f_i and its transmit power level p_i to maximize its utility function. Based on our problem definition, all players have an identical utility function of the mean sum downlink achievable rate:

$$U(\mathbf{f}, \mathbf{p}) = \sum_{i \in B_f} \tilde{R}_i(f_i, p_i) \tag{12}$$

where B_f is the index set of all the femto BSs in the game, and $\mathbf{f}$ and $\mathbf{p}$ are the vectors representing all the BSs' operating frequency channels and transmit power levels, respectively. In order to maximize the utility function, each player i chooses a best joint power-frequency action vector $a_i = (p_i, f_i)$ from action space $A_i = \mathbb{F} \times \mathbb{P}$ where $\mathbb{F}$ and $\mathbb{P}$ are sets of frequency channels and power levels, respectively.

For the constraints, the SINR of macrocell user j which is associated with macro BS i and located at l_j within the outage area of the considered femtocell, i.e., η_j, should be secured over η_{th} to ensure the link quality. It can be represented as follows:

$$I(f_i) := \sum_{k \in B_m(f_i)} I_k(l_j) + \sum_{k \in B_f(f_i)} I_k(l_j), \tag{13}$$

$$\eta_j(f_i) = \frac{g_{ij} P}{N_0 + I(f_i)} \tag{14}$$

where f_i is the operating frequency channel of macro BS i, and $I(f_i)$ is the interference from all the macro and femto BSs operating in f_i. We assume that the macro BS uses a fixed transmit power of P. In the viewpoint of the game,

[1] The order of action and the action policy can be selected more freely within some known policies. For instance, the potential game will converge where the order of players' actions is random (referred to as asynchronous order), and a player randomly chooses its action if the action increases its utility compared with the current utility (referred to as the random better response).

Algorithm 2. The Proposed Operation of SON Scheme

Initialization procedure

1: **for** $i \leftarrow 1,\ i \leftarrow i+1,\ i \leq |B_f|$ **do**
2: Femto BS i:
3: Transmits the preamble with its maximum power
4: Other femto BSs:
5: 1) Measure the channel gain from femto BS i
6: 2) Send the results to the management server

Interaction procedure

1: Do the interaction for the game, e.g., Algorithm 1

the constraints due to the macrocell users limit the action space of a femto BS to the feasible space. Then, the considered problem can be formulated as follows:

$$(\mathbf{f}^*, \mathbf{p}^*) = \arg\max_{\mathbf{f},\mathbf{p}} U(\mathbf{f}, \mathbf{p}) \tag{15}$$

$$\text{s.t.} \quad \eta_j(f_i) > \eta_{th} \qquad \forall j \in U_{out} \tag{16}$$

where U_{out} is the index set of macrocell users in the outage area of the considered femtocell.

In this work, the order of players' actions is assumed to be random. A player is randomly chosen in a round, and the player chooses the action which makes its utility maximized (referred to as best response policy). For the practical operation, we assume that there is a management server which is in charge of managing and exchanging the data, clustering SON groups, and supervising the SON operation for each group. Such a management server will be practically mandatory and can make the proposed scheme more applicable and practical. Summarily, the proposed game algorithm is explained in Algorithm 1. First, all the femto BSs initialize their action randomly, and prepare for the game by initializing their algorithm parameters. When the game starts, each femto BS increases its total iteration counter, $titr_i$, get the current network state, cst_i, by measurement, and waits for the decision epoch. At the decision epoch, each femto decides whether it should make a decision at this time by the decision order represented as $DEC(-)$. Each femto BS which decides to make a decision choose its action considering its macrocell user constraints, where $CONST(-)$ is the function to check whether the selected temporal action, $tact_i$, satisfies all the macrocell user constraints. In addition, $UTIL(-)$ is the function to calculate the utility. Next, if no action satisfies the constraints, i.e., $cret_i = 0$, the femto BS selects random action and waits for the next decision epoch. Otherwise, the femto BS checks whether its convergence utility, $cutil_i$, should be updated compared with the temporal best utility, $butil_i$. Then, it also waits for the next decision epoch.

5 Operation of the Proposed SON Scheme

For a distributed and practical operation of the proposed SON scheme, the operational procedure needs to be considered, and there mainly arise three issues;

1) the common utility function, $U(\mathbf{f}, \mathbf{p})$ in Eq. (12), should be shared among the femto BSs, 2) the decision results, i.e., $\mathbf{f}$ and $\mathbf{p}$, should be delivered to all the femto BSs, and 3) the macrocell users' feedback, η, should be reflected to the femto BSs' decision. For the first and second issues, we need to focus on U in Eq. (12) which is a function of $\widetilde{\gamma}$ in Eq. (9). Then, in order to build U, each femto BS should have all g and p values of other BSs in Eqs. (8) and (9). Basically, g in Eq. (9) is a given value for each femto BS. However, g's in Eq. (8) should be measured before being exchanged.

The proposed SON scheme can be divided into two procedures, i.e., initialization and interaction proceduresAlgorithm 2. During the initialization procedure, the femto BSs measure the channel gain values among them, i.e., g's in Eq. (8). In a round robin manner, each femto BS transmits its preamble with a maximum power and other femto BSs measure the channel gain from the femto BS. Such a measurement procedure repeats until all the channel gain information is measured. Based on the exchanged information, the required objective and constraints for the game can be generated. Next, during the interaction procedure, the femto BSs conduct the proposed game as described in Algorithm 1. The decision results of other femto BSs can be measured during the game, and then no more backhaul communication is required during the game.

The proposed SON operation could be completely applied for the periodic operation shown in Fig. 1. However, for the initial and event-based operation, it might not be proper since it is a burden to repeat the measurement procedure, for instance, whenever a new femto BS enters the network. Then, the corresponding femto BS, e.g., the newly entered femto BS, only selects its frequency channel and power lever without any interaction with other femto BSs. For instance, the femto BS can select the frequency channel which is most idle and set the transmit power level to a given value. Such femto BSs will join the next periodic SON operation, and interact with other femto BSs to optimize the network.

For the third issue, i.e., the macrocell users' feedback, the femto BSs need to cooperate with the macro BSs and macrocell users. For the operation, we assume that the femto BSs can have the scheduling information, e.g., a scheduling map of IEEE 802.16e, of the macro BS. Based on the scheduling information, the femto BSs can find the macrocell users in the outage area around their service coverage by detecting the uplink transmission of the macrocell users. Since we cannot directly find the macrocell users from the downlink transmission, such an uplink detection is one of the feasible and reasonable ways to find the macrocell users near a femto BS.

Based on such operations, the femto BS can obtain the channel gain between the femto BS itself and the macrocell users which are identified. The femto BSs use the channel gain information as the constraints to the macrocell users described in Eq. (16) when the femto BSs conducts the SON operation. Basically, the proposed SON scheme can work based on the described operation. However, as explained in Section 4, the performance of the proposed game is not optimal, and it can be improved.

Algorithm 3. Tabu Game Algorithm

Initialization, $\forall i \in B_f$

$\mathbf{T}_i \leftarrow \emptyset,\ act_i \leftarrow (RND(f), RND(p))\,,\ act_i \in \mathbb{F} \times \mathbb{P}$
$titr_i \leftarrow 0,\ citr_i \leftarrow 0,\ cutil_i \leftarrow 0,\ cact_i \leftarrow (0,0)$

Iteration, $\forall i \in B_f$

while $titr_i < titr_{th}$ **and** $citr_i < citr_{th}$ **do**
  $titr_i \leftarrow titr_i + 1, butil_i \leftarrow 0, bact_i = (0,0), cret_i \leftarrow 0$
  Gets the current network state: $cst_i \leftarrow (\mathbf{f}_{-i}, \mathbf{p}_{-i})$
  Waiting for a decision epoch
  if $DEC(|B_f|) \neq$ success **then**
    continue
  else
    for $tact_i \leftarrow (f,p),\ \forall (f,p) \in \mathbb{F} \times \mathbb{P}$ **do**
      if $CONST(tact_i, cst_i) = 1$ **then**
        continue
      if $CONST(tact_i, cst_i) = 0$ **and** $cret_i = 0$ **then**
        $cret_i \leftarrow 1$
      if $UTIL(tact_i, cst_i) > butil_i$ **then**
        $butil_i \leftarrow UTIL(tact_i, cst_i),\ bact_i \leftarrow tact_i$
    if $cret_i = 0$ **then**
      $act_i \leftarrow (RND(f), RND(p))\,,\ act_i \in \mathbb{F} \times \mathbb{P}$
      continue
    $tcnt_i \leftarrow 0$
    while $CTABU(\mathbf{f}, \mathbf{p}_{-i}) = 1$ **and** $tcnt_i < tcnt_{th}$ **do**
      $act_i \leftarrow (RND(f), RND(p))\,,\ act_i \in \mathbb{F} \times \mathbb{P}$
      $tcnt_i \leftarrow tcnt_i + 1$
    if $cutil_i < butil_i$ **then**
      $citr_i \leftarrow 0, cutil_i \leftarrow butil_i,\ cact_i \leftarrow bact_i$
    else
      $citr_i \leftarrow citr_i + 1$
    $act_i \leftarrow bact_i$
    $ATABU(\mathbf{T}_i, \mathbf{f}, \mathbf{p}_{-i})$

6 Tabu Search Extended Game Algorithm

Even though the proposed game algorithm in Section 4 converges to a Nash equilibrium, it does not guarantee a global optimality, since the problem in consideration is non-convex and NP-hard due to the non-linearity of the power control and the combinatorial property of the channel selection. Frankly speaking, even if we consider only the DFS problem, the problem is NP-hard where no algorithm can give the global optimal solution in polynomial time. Then, in computer science, metaheuristic is developed in order to improve the solutions of such combinatorial and/or non-linear problems [15]. In general, many metaheuristic algorithms mainly are based on the random processes in order to escape local optima even though such a randomness might deteriorates the objective values of the problem in consideration temporarily. They try to improve the

Table 1. System parameters for the simulation

P_{max}	20 dBm	P_{min}	-3 dBm
Power levels	10	Num. of freq. ch.	3
Size of open area	200 x 200 m^2	N_0	-95 dBm
Building size	50 x 50 m^2	Penetration loss	12 dB
$P_{macroBS}$	43 dBm	Interf. threshold	1 dB

solutions by iteratively solving the problem with manipulated solution spaces. However, such metaheuristic algorithms also cannot guarantee a global optimality, but they only give better solutions compared with local search algorithms. In this work, in order to attempt to achieve a global optimality, we enhance the proposed game algorithm by using a Tabu search, which is one of well-known metaheuristic algorithms [16].

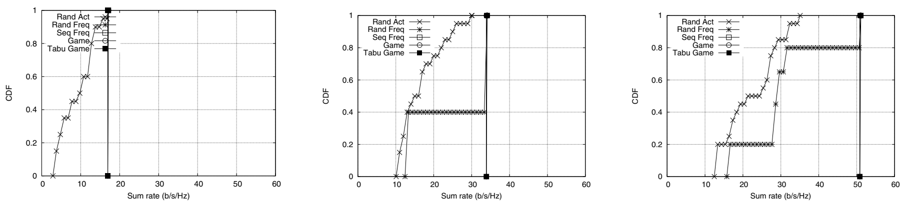
In the viewpoint of an algorithm structure, a metaheuristic algorithm is an extended local search algorithm, which allows to choose a random solution under some given conditions. Especially, a Tabu search algorithm uses an additional memory referred to as a Tabu list which stores previously visited solutions and helps the algorithm find new solutions by preventing it from reselecting the stored solutions. The usage of a memory enables an effective search compared with the algorithms which heavily depends on a random process without a memory. In this work, the proposed game algorithm is considered a distributed local search algorithm, and its performance can be improved by using a Tabu search algorithm. Theoretically, the extension is simple, and it only changes the searching procedure.

The Tabu search integrated with a game has an effect that expands the searching space so as to leverage player's opportunity to reach the region where the optimal point lies over the Nash equilibrium points. The main point of the extension is considering the distributed property of the proposed game algorithm. In other words, a Tabu list also needs to be distributed, and then each femto BS has its own Tabu list and automatically updates its Tabu list. Note that, for a distributed Tabu list, the important issue is what should be elements of the Tabu list. In this work, we consider a vector which is composed of the decision maker's operating frequency channel and the interference environment. For instance, the Tabu list for femto BS i can be defined as $\mathbf{T}_i$, and an element for $\mathbf{T}_i$ is defined as follows:

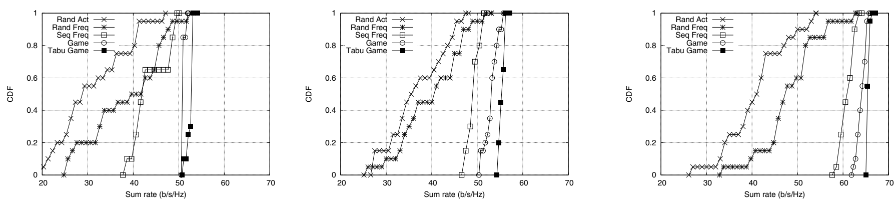
$$(\mathbf{f}, \mathbf{p}_{-i}) \tag{17}$$

The reason why its transmit power level is not included in the vector is that the decision will be identical under the same decision rule when the femto BS meets the same interference environment. In addition, for such a case, it is more efficient to perturb the interference environment if the femto BS chooses a frequency channel among other frequency channels to find a new search space.

Algorithm 3 presents the proposed Tabu game. Basically, the operation procedure is almost same as Algorithm 1 since it is based on it. The difference from the original game is that the action set of a player is limited by its Tabu list, and the player can only choose its action which is not included in its Tabu list. For a



(a) One random femto BS (b) Two random femto BSs (c) Three random femto BSs



(d) Six random femto BSs (e) Nine random femto BSs (f) Twelve random femto BSs

Fig. 5. The proposed schemes are compared with other schemes with different numbers of the installed femto BSs.

Tabu game, all players additionally initialize their Tabu list in the initialization procedure, and starts an iteration procedure. During the iteration procedure, for instance, femto BS i additionally check its Tabu list by $CTABU(-)$ in order to decide its action. Then, if the selected action is in its Tabu list, $\mathbf{T}_i$, femto BS i randomly selects an action. At the end of the decision procedure, femto BS i adds the element in $\mathbf{T}_i$ by using $ATABU(-)$ to avoid the reselection of the action, and wait for the next decision epoch. Finally, a Tabu game algorithm remembers the best solution, and decides it as its final decision at the end of the iteration.

7 Performance Evaluation

In this section, we evaluate the proposed game and Tabu game algorithms. First, we compare the performance of the proposed algorithms with others. In order to show the pure performance gain of the proposed algorithms, the evaluation is conducted without considering the constraints of the macrocell users. Second, the proposed algorithm is evaluated in a more practical simulation environment to estimate the expected performance for the real installation. For this simulation, the simulation environment and the theoretical performance bound in [12] are considered for comparison.

For the first simulation, we assume that femto BSs are deployed in a 200 m square-shaped area. The transmit power of a femto BS is equally quantized into ten levels ranging from −3 dBm to 20 dBm in a dB scale. Three orthogonal frequency channels are considered, and all the channel models follow the

ITU-R M.1225 model [3]. Each femto BS adapts its transmit power and operating frequency channel by following the best response, and the order of decision is randomly determined. The size of each femto BS's Tabu list is assumed to be unlimited, since the price of the memory is very cheap compared with the past days. We assume that femto BSs are randomly located in the considered area, and there is no macro BS and macrocell user. Based on such assumptions, the performance of the proposed scheme could be purely compared with other schemes. Those parameters are summarized in Table 1.

For the comparison, we consider the following algorithms:

1. **Random frequency and power selection (Rand Act):** Each femto BS selects its transmit power and frequency channel randomly.
2. **Random frequency selection (Rand Freq):** Each femto BS selects its frequency channel randomly with its maximum transmit power.
3. **Sequential frequency selection (Seq Freq):** Femto BSs sequentially select their frequency channel with their maximum transmit power. When they select the power and frequency channel, they greedily try to maximize their own utility function.

In Fig. 5, The results of the performance comparison are depicted based on the CDF of the sum rate, i.e., the sum objective values of all the femto BSs when they converge. In the figure, there are six subfigures according to the number of femto BSs. When the number of femto BSs increases one to three, the number of femto BSs is less than or equal to the number of the orthogonal frequency channels. Then, the performance increases as the number of femto BSs increases. For the proposed algorithms, since all three femto BSs can orthogonally select one of the frequency channels, the obtained performance linearly increase according to the number of the frequency channels. For those cases, the performance of the proposed game and Tabu game algorithms is identical. However, other random algorithms cannot achieve the maximum performance since they do not guarantee the orhogonal channel selection.

When the number of femto BSs is greater than three, the performance dose not linearly increase since there is no more orthogonal frequency channel from the fourth femto BS. Nevertheless, the performance can increase as the number of femto BSs increases since the chance that more femto BSs are located in the preferred locations increases. However, the performance will be saturated eventually when the number of femto BSs is large enough. In these cases, the Tabu game algorithm outperforms all other algorithms. One interesting result is that the proposed game algorithm and the Seq Freq algorithm also give relatively good performance. Such a tendency becomes clearer as the number of femto BSs increases, especially for the Seq Freq algorithm. It means that as the number of femto BSs increases, the performance could be reasonably improved only by a proper frequency channel selection, even though high performance discrepancy still exists from the proposed algorithms. The proposed Tabu game algorithm always shows the best performance compared other algorithms, with a small variance of the objective values. On the other hand, the CDF graphs of two

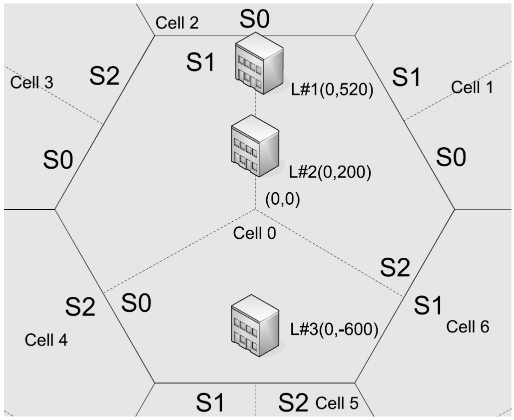


Fig. 6. Simulation environment for the second simulation

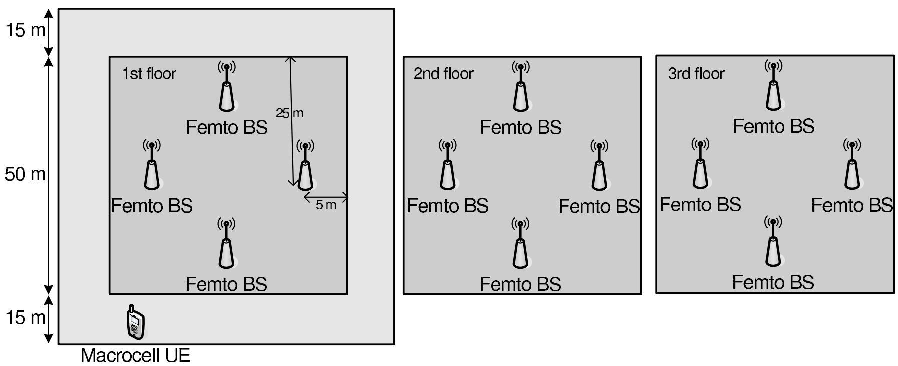
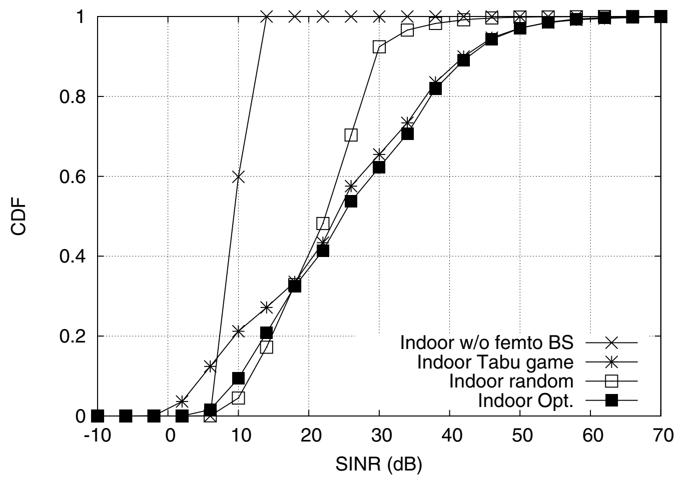


Fig. 7. Locations of femto BSs inside the building

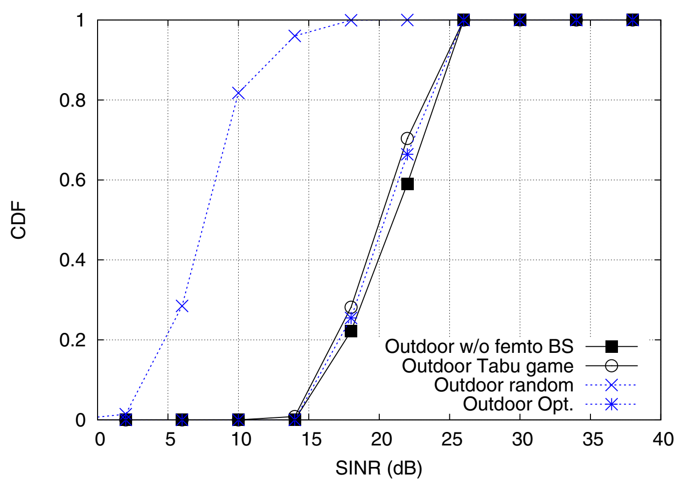
random selection schemes are very similar and are widely spread, which are not proper for the practical environment.

In Fig. 8, the proposed Tabu game algorithm is evaluated in the same simulation environment of the referenced paper [12]. A conventional multi-cell honeycomb structure is considered, and each macrocell is divided into three sectors denoted by S0, S1, and S2 as shown in Fig. 6. The sector is labeled by Sx ($x = 0, 1, 2$) and it uses the $(x + 1)$th frequency channel out of three available channels. We assume that all macro BSs has 43 dBm transmit power. In this simulation, the building is assumed to be located in the L#2 location where the macrocell users are served via frequency channel 1 and 2. We assume that the size of building is 50 x 50 m^2, and the street width is 30 m where the street is the same as the outage area in this work. Twelve femto BSs are located in the three story building as shown in Fig. 7.

Assuming that both macrocell and femtocell networks are perfectly synchronized, the femto BS plays as a downlink interferer to users in a macrocell net-



(a) The CDF of SINR, indoor case



(b) The CDF of SINR, outdoor case

Fig. 8. The CDF of SINR, when the building is located at L#2

work, and this is the major difference of the simulation environment compared with the first simulation. Then, the femto BSs should satisfy the interference constraints to the macrocell users near the building. The interference threshold for the performance degradation of the macrocell users are assumed to be 1 dB. The penetration loss is considered 12 dB, and the simulation parameters are also summarized in Table 1.

In Fig. 8, four pairs of SINR CDF graphs are depicted for the cases without femto BSs, with femto BSs configured by a Tabu game algorithm, with femto BSs by a Rand Act algorithm, and with femto BSs configured optimally. As shown in Fig. 8(a), for the case when there is no femto BS in the building, the average SINR is low compared with other cases. However, the average SINR increases with the deployment of the femto BSs, and the Tabu game algorithm almost achieves the optimal performance. Interestingly, the Rand Act algorithm seems to achieve high performance, however, it is not desirable since it dose not consider the interference to the macrocell users. In Fig. 8(b), the CDF of outdoor SINR are depicted, except the Rand Act algorithm case, all other algorithms meet the interference threshold. As a conclusion, the Tabu game algorithm is expected to achieve the high performance for the practical environment.

8 Conclusion

In this work, we consider a self-organizing femtocell network performing TPC and DFS for the downlink of a femtocell network. First, the classification of the femtocell network is considered, and we model the downlink of the femtocell network in consideration. For the practical application of the self-organizing femtocell network, we describe the proposed operational procedures. Basically, we develop the self-organizing femtocell network based on a potential game which guarantees the convergence, and we develop a distributed strategy of femto BSs for adapting their air-parameters. Additionally, the global optimality issue is also addressed by proposing a Tabu search game algorithm. Compared with other expected self-organizing schemes, the evaluation shows that the proposed algorithms achieve the higher gain in average and small variance. In addition, based on the simulation results, the proposed game and Tabu game algorithms are highly expected to be proper for the practical deployment.

References

[1] Alouini, M., Goldsmith, A.: Area Spectral Efficiency of Cellular Mobile Radio Systems. IEEE Trans. Vehicular Technology 48(4), 1047–1066 (1999)

[2] Chandrasekhar, V., Andrews, J., Gatherer, A.: Femtocell Networks: A Survey. IEEE Communications Magazine 46(9), 59–67 (2008)

[3] Requirements Related to Technical Performance for IMT-Advanced Radio Interface(s), ITU-R Std. Report M.2134 (December 2008)

[4] The 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC) protocol specification (Release 8), 3GPP Std. TS 36.321 v8.1.0 (December 2007)

[5] IEEE 802.16m System Description Document (SDD), IEEE Std. IEEE 802.16m-09/0034r3 (June 2010)

[6] Zeng, H., Zhu, C., Chen, W.: System Performance of Self-Organizing Network Algorithm in WiMAX Femtocells. In: Proc. WICON 2008, Hawai, US (November 2008)

[7] Guvenc, I., Jeong, M., Watanabe, F., Inamura, H.: A Hybrid Frequency Assignment for Femtocells and Coverage Area Analysis for Co-Channel Operation. IEEE Communincations Letters 12(12), 880–882 (2008)

[8] Chandrasekhar, V., Andrews, J., Muharemovic, T., Shen, Z., Gatherer, A.: Power Control in Two-Tier Femtocell Networks. IEEE Trans. Wireless Communications 8(8), 4316–4328 (2009)
[9] Jo, H., Mun, C., Moon, J., Yook, J.: Interference Mitigation Using Uplink Power Control for Two-Tier Femtocell Networks. IEEE Trans. Wireless Communications 8(10), 4906–4910 (2009)
[10] Arulselvan, N., Ramachandran, V., Kalyanasundaram, S., Han, G.: Distributed Power Control Mechanisms for HSDPA Femtocells. In: Proc. IEEE VTC 2009-Spring, Barcelona, Spain (April 2009)
[11] Li, X., Qian, L., Kataria, D.: Downlink Power Control in Co-Channel Macrocell Femtocell Overlay. In: Proc. CISS 2009, Baltimore, MD (March 2009)
[12] Han, K., Choi, Y., Na, M., Kim, D., Choi, S., Han, K.: Optimization of Femtocell Network Configuration Under Interference Constraints. In: Proc. WiOpt, Seoul, Korea (June 2009)
[13] Neel, J.: Analysis and Design of Cognitive Radio Networks and Distributed Radio Resource Management Algorithms. Ph.D. dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA, US (September 2006)
[14] IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands and Corrigendum 1, IEEE Std. 802.16e-2005 and 802.16-2004/Cor 1-2005 (February 2006)
[15] Bertsekas, D.: Nonlinear programming. Athena Scientific (1999)
[16] Glover, F., Laguna, M.: Tabu Search. Kluwer (1997)