Downlink Resource Allocation for a Network using Femto-Base Stations as Relays to Macro-Users

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Abstract

In this paper, we propose a resource allocation algorithm for the downlink of a two-tier wireless network in which femto-base stations are used as relays to macro-users. Simulation results show that the proposed algorithm has higher fairness index than the greedy scheme.

1. Introduction

In a wireless network, femtocells increase capacity and reduce the traffic load of macro-base station (MBS) by using low-cost femto-base stations (FBSs) to serve dedicated femto-users (FUs) [1]. However, MBS and FBSs cause inter-tier interference to FUs and macro-users (MUs), respectively, if FUs use the same spectrum as MUs [2].

It is shown in [3], [4] that the interference from a FBS to a MU is eliminated if the FBS is used as a relay to the MU. In a network using FBSs as relays to MUs, the problem of resource allocation to MUs and FUs has not been investigated.

In this paper, we consider the downlink of a two-tier network where FBSs are used as relays to MUs. An optimization problem is formulated to maximize the total net utility of all users under power constraints of base stations and a resource allocation algorithm is proposed to solve the formulated problem.

The rest of this paper is organized as follows. We describe the system model in section 2, formulate the optimization problem in section 3, and propose the resource allocation algorithm to solve it in section 4. We present computer simulation results in section 5 and draw conclusions in section 6.

2. System Model

Consider the downlink of a two-tier wireless network with a macrocell in the first tier and J femtocells in the second tier. Assume that there are K MUs in macrocell and L_j , $j=1 \ldots J$, FUs in femtocell j . Assume that femtocells do not overlap with each other and that interference from a FBS to a MU is negligible if the MU is outside the coverage of that FBS [5]. Assume that MUs and FUs share spectrum of bandwidth W which is divided into M subcarriers of bandwidth $B = W / M$ each. Assume that MBS and FBSs transmit at the same time in time-slots of duration T .

Suppose that MBS assigns subcarrier m to MU k . If MBS assigns FBS j as a relay to MU k , data is transmitted to MU k in two phases of equal duration $T/2$. In the first phase, MBS transmits data to MU k and FBS j over subcarrier m with transmit power P^{M} . In the second phase, FBS j decodes and forwards the data received from the MBS to MU k over subcarrier m with transmit power P^{F}. MU k combines data received in the first and second phases by maximal ratio combining (MRC) [6] If MBS does not assign any FBS as a relay to MU k , it transmits data to MU k in a single phase of duration T over subcarrier m with transmit power P^{M} .

Suppose that FBS j assigns the subcarrier m to FU l_j . FBS j transmits data to FU l_j in a single phase of duration T over subcarrier m with transmit power P^{F} .

3. Problem Formulation

The utility function of a user is defined as $\mathrm{U}(r) = \dfrac{r^{1-\alpha} - 1}{1-\alpha}$ where $\alpha \in [0, \infty)$ is a fairness parameter and the utility function represents the utility of data rate r to the user. A higher value of α leads to a more fair resource allocation to all users but a lower sum rate, and vice versa [7]. The cost function of a user is defined as $\mathrm{C}(P) = P$ and represents the cost incurred by all the base stations in transmitting data to the user with a total transmit power P . The net utility of a user is defined as $\mathrm{U}_{\mathrm{net}}(r, P) = \mathrm{U}(r) - \mu \mathrm{C}(P)$ where μ is the weight of the cost function of the user [8].

Let δ^{M}_{km} , $\pi^{\mathrm{F}_j}_{km}$, and $\delta^{\mathrm{F}_j}_{l_j m}$ denote binary indicator variables. If MBS assigns subcarrier m to MU k , $\delta^{\mathrm{M}}_{km} = 1$, and $\delta^{\mathrm{M}}_{km} = 0$, otherwise. If MBS assigns FBS j as a relay to transmit data to MU k over subcarrier m , $\pi^{\mathrm{F}_j}_{km} = 1$, and $\pi^{\mathrm{F}_j}_{km} = 0$, otherwise. If FBS j assigns subcarrier m to FU l_j , $\delta^{\mathrm{F}_j}_{l_j m} = 1$, and $\delta^{\mathrm{F}_j}_{l_j m} = 0$, otherwise. Then, the optimization problem to maximize the total net utility of users is formulated as

$$\begin{aligned}\max_{\left(\boldsymbol{\Delta}^{\mathbf{M}},\boldsymbol{\Pi}^{\mathbf{F}},\boldsymbol{\Delta}^{\mathbf{F}}\right)} \; & \left\{\sum_{k=1}^{K}\sum_{m=1}^{M}\delta_{km}^{\mathrm{M}}\left(1-\pi_{km}^{\mathrm{F}_j}\right)\mathrm{U}_{\mathrm{net}}\left(r_{km}^{\mathrm{M}},P^{\mathrm{M}}\right)\right. \\ & +\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m=1}^{M}\delta_{km}^{\mathrm{M}}\pi_{km}^{\mathrm{F}_j}\,\mathrm{U}_{\mathrm{net}}\left(r_{km}^{\mathrm{M,F}_j},P^{\mathrm{M}}+P^{\mathrm{F}}\right) \\ & \left.+\sum_{j=1}^{J}\sum_{l_j=1}^{L_j}\sum_{m=1}^{M}\delta_{l_j m}^{\mathrm{F}_j}\,\mathrm{U}_{\mathrm{net}}\left(r_{l_j m}^{\mathrm{F}_j},P^{\mathrm{F}}\right)\right\}\end{aligned} \quad (1)$$

$$\text{subject to: } \sum_{k=1}^{K}\delta_{km}^{\mathrm{M}}\le 1,\ \forall m, \quad (2)$$

$$\sum_{l_j=1}^{L_j}\delta_{l_j m}^{\mathrm{F}_j}\le 1,\ \forall j,m, \quad (3)$$

$$\sum_{k=1}^{K}\delta_{km}^{\mathrm{M}}\pi_{km}^{\mathrm{F}_j}\le 1,\ \forall j,m, \quad (4)$$

$$\sum_{j=1}^{J}\delta_{km}^{\mathrm{M}}\pi_{km}^{\mathrm{F}_j}\le 1,\ \forall k,m, \quad (5)$$

$$\pi_{km}^{\mathrm{F}_j}\left(1-\delta_{km}^{\mathrm{M}}\right)=0,\ \forall j,k,m, \quad (6)$$

$$\delta_{l_j m}^{\mathrm{F}_j}\sum_{k=1}^{K}\delta_{km}^{\mathrm{M}}\pi_{km}^{\mathrm{F}_j}=0,\ \forall j,l_j,m, \quad (7)$$

$$\delta_{km}^{\mathrm{M}},\ \pi_{km}^{\mathrm{F}_j},\ \delta_{l_j m}^{\mathrm{F}_j}\in\{0,1\},\ \forall j,l_j,k,m, \quad (8)$$

where $\boldsymbol{\Delta}^{\mathbf{M}}=\left\{\delta_{km}^{\mathrm{M}},\forall k,m\right\}$, $\boldsymbol{\Pi}^{\mathbf{F}}=\left\{\pi_{km}^{\mathrm{F}_j},\forall j,k,m\right\}$, $\boldsymbol{\Delta}^{\mathbf{F}}=\left\{\delta_{l_j m}^{\mathrm{F}_j},\forall j,l_j,m\right\}$, r_{km}^{M} is the data rate of MU k over subcarrier m if it is not assigned any FBS as a relay, $r_{km}^{\mathrm{M,F}_j}$ is the data rate of MU k over subcarrier m if it is assigned FBS j as a relay, and $r_{l_j m}^{\mathrm{F}_j}$ is the data rate of FU l_j in femtocell j over subcarrier m. The constraints (2) and (3) imply that a subcarrier is assigned to at most one user in a cell. The constraint (4) implies that a FBS is assigned as a relay to at most one MU over each subcarrier. The constraint (5) implies that at most one FBS is assigned as a relay to a MU over each subcarrier. The constraint (6) implies that if a subcarrier is not assigned to a MU, then, that MU is not assigned any FBS as a relay over that subcarrier. The constraint (7) implies that subcarrier m is not assigned to any FU of a femtocell whose FBS is assigned as a relay to a MU over subcarrier m.

4. Proposed Subcarrier and Relay Assignment Algorithm

Let Y_k denote a variable such that $\mathrm{Y}_k=j$ if MU k is in coverage of femtocell j and $\mathrm{Y}_k=0$, otherwise. Let $\mathrm{U}_{\mathrm{tot},km}^{(1)}$ denote the total net utility of all users over subcarrier m assuming that MU k is not assigned any relay and that subcarrier m is assigned to a FU in femtocell j, $j=\mathrm{Y}_k$. Let $\mathrm{U}_{\mathrm{tot},km}^{(2)}$ denote the total net utility of all users over subcarrier m assuming that MU k is assigned FBS j as a relay and that subcarrier m is not assigned to any FU in femtocell j, $j=\mathrm{Y}_k$.

The optimal subcarrier and relay assignment to the users can be obtained by an exhaustive search over all possible subcarrier assignments to MUs and FUs and relay assignments to MUs. Since high computational complexity is required to obtain the optimal assignment, a suboptimal subcarrier and relay assignment algorithm is proposed and is shown in Algorithm 1 on the next page. All variables are initially set to 0. Each subcarrier is assigned in two steps which are described for subcarrier m and are repeated for the remaining subcarriers.

In the first step, the net utility of each FU over subcarrier m is computed assuming that there is inter−tier interference from MBS to FUs over subcarrier m. In each femtocell, subcarrier m is assigned to the FU with the largest positive net utility over it. The subcarrier m is not assigned to any FU in a femtocell if no FU in the femtocell has a positive net utility over it. The total net utility of all FUs over subcarrier m, $\mathrm{U}_{\mathrm{tot},m}^{\mathrm{F}}$, is computed.

In the second step, the maximum total net utility of all users over subcarrier m, $\mathrm{U}_{\max,m}$, is computed. If $\mathrm{U}_{\max,m}>\mathrm{U}_{\mathrm{tot},m}^{\mathrm{F}}$, subcarrier m is assigned to the MU k^* such that the total net utility of all users over subcarrier m is maximized. If $\mathrm{U}_{\mathrm{tot},k^*m}^{(2)}>\mathrm{U}_{\mathrm{tot},k^*m}^{(1)}$, the total net utility of all users over subcarrier m is maximized by assigning FBS j, $j=\mathrm{Y}_{k^*}$, as a relay to MU k^*. If $\mathrm{U}_{\max,m}\le\mathrm{U}_{\mathrm{tot},m}^{\mathrm{F}}$, subcarrier m is not assigned to any MU and $k^*=0$. The net utility of each FU over subcarrier m is computed assuming that there is no inter−tier interference from MBS to FUs over subcarrier m. The subcarrier assignment to FUs, as described in the first step, is repeated.

5. Simulation Results

Suppose that 10 femtocells are uniformly distributed in a macrocell and that there are 300 subcarriers with a bandwidth of $1\,\mathrm{kHz}$ each. The path−loss model recommended by 3GPP LTE group [9] is adopted. Jain's fairness index is used to compare the fairness of resource allocation to MUs and FUs for different values of the fairness parameter α [10]. The performance of the proposed algorithm is compared with a greedy scheme.

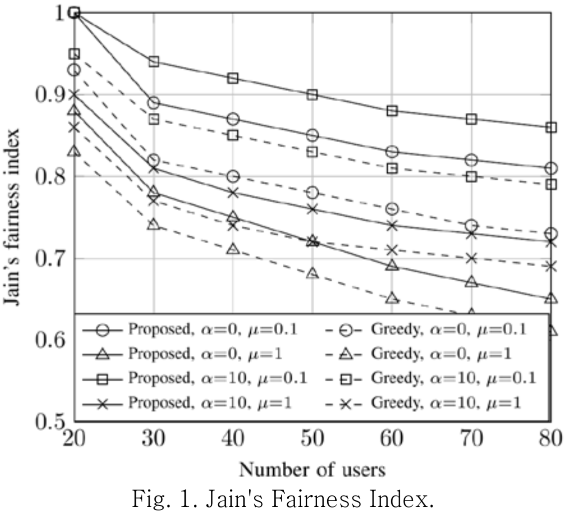

Fig. 1. Jain's Fairness Index.

Algorithm 1: Proposed subcarrier and relay assignment algorithm

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1.  Initialize $\delta_{km}^{\mathrm{M}} = \pi_{km}^{\mathrm{F}_j} = \delta_{l_j m}^{\mathrm{F}_j} = 0, \forall j, k, l_j, m$.
2.  for $m = 1 : M$ do
3.      Step 1:
4.      Compute $\mathrm{U}_{\mathrm{net}}\left(r_{l_j m}^{\mathrm{F}_j}, P^{\mathrm{F}}\right), \forall l_j, j$ considering
        inter-tier interference from MBS to FUs
        over subcarrier $m$.
5.      for $j = 1 : J$ do
6.          $l_j^* = \arg\max_{l_j} \left\{ \mathrm{U}_{\mathrm{net}}\left(r_{l_j m}^{\mathrm{F}_j}, P^{\mathrm{F}}\right) \right\}$.
7.          if $\mathrm{U}_{\mathrm{net}}\left(r_{l_j^* m}^{\mathrm{F}_j}, P^{\mathrm{F}}\right) > 0$ then $\delta_{l_j^* m}^{\mathrm{F}_j} = 1$.
8.      $\mathrm{U}_{\mathrm{tot},m}^{\mathrm{F}} = \sum_{j=1}^{J} \delta_{l_j^* m}^{\mathrm{F}_j} \mathrm{U}_{\mathrm{net}}\left(r_{l_j^* m}^{\mathrm{F}_j}, P^{\mathrm{F}}\right)$.
9.      Step 2:
10.     $\mathrm{U}_{\max,m} = \max\left\{ \max_{(i,k)} \left\{ \mathrm{U}_{\mathrm{tot},km}^{(i)} \right\}, \mathrm{U}_{\mathrm{tot},m}^{\mathrm{F}} \right\}, i = 1, 2$.
11.     if $\mathrm{U}_{\max,m} > \mathrm{U}_{\mathrm{tot},m}^{\mathrm{F}}$ then
12.         $k^* = \arg\max_{(k)} \left\{ \max_{(i)} \left\{ \mathrm{U}_{\mathrm{tot},km}^{(i)} \right\} \right\}, i = 1, 2$.
13.         $\delta_{k^* m}^{\mathrm{M}} = 1$.
14.         $j = \mathrm{Y}_{k^*}$.
15.         if $\mathrm{U}_{\mathrm{tot},k^* m}^{(2)} > \mathrm{U}_{\mathrm{tot},k^* m}^{(1)}$ then
16.             $\pi_{k^* m}^{\mathrm{F}_j} = 1$.
17.             $\delta_{l_j m}^{\mathrm{F}_j} = 0, \forall l_j$.
18.     else
19.         $k^* = 0$.
20.         Compute $\mathrm{U}_{\mathrm{net}}\left(r_{l_j m}^{\mathrm{F}_j}, P^{\mathrm{F}}\right), \forall l_j, j$ considering
            inter-tier interference from MBS to FUs
            over subcarrier $m$.
21.         Repeat 5-7.
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Fig. 1 on the previous page shows Jain's fairness index. It is shown that the proposed algorithm has higher fairness index than the greedy scheme. It is shown that the proposed algorithm has lower fairness index for $\alpha = 0$ than for $\alpha = 10$. It is shown that the proposed algorithm has higher fairness index for smaller values of μ and vice versa.

6. Conclusion

In this paper, we consider the downlink of a two-tier network consisting of a macrocell and several femtocells where femtocells are used as relays to MUs. We formulate an optimization problem to maximize the total net utility of all users. We propose a resource allocation algorithm to solve the formulated problem. Simulation results show that the proposed algorithm has higher fairness index than the greedy scheme.

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