A RADIO RESOURCE MANAGEMENT STRATEGY FOR DOWNLINK COOPERATION IN DISTRIBUTED NETWORKS

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ABSTRACT

Downlink cooperation between Base Stations is a simple, efficient alternative to macrodiversity for providing QoS continuity during mobility in distributed cellular networks. It brings cooperation diversity and only requires data forwarding between Base Stations. This paper presents a strategy for downlink cooperation triggering, resource allocation and power control in an OFDMA-based system. Power control aims at maximizing the equivalent capacity that is achieved thanks to the diversity brought by relaying, while taking into account intercell interference. We use an iterative method which dedicates a proportion of the total power to relayed users. Simulation results show that our method increases capacity at any load. It importantly reduces the rejection probability thanks to SIR increase of users at cell's border. The paper also shows that cooperation should be limited to cell-border users for restricting additional resource consumption, and that it should make use of diversity as much as possible.

I. INTRODUCTION

The latest developments in standardization bodies show the requirement for reducing latency and cost in future cellular networks, by limiting the number of network nodes along the data [1]. The most commonly agreed way is to set all Radio Resource Management (RRM) decisions into the Node B, and to suppress the RNC. This enables a faster reaction and is well adapted for efficient scheduling methods in OFDMA, but it removes the possibility to perform macrodiversity. In this paper, we propose a method to enable smooth handover between cells, without requiring a global controller like the RNC. Our method is consequently a possible alternative to macrodiversity, and is particularly suited for distributed cellular networks. It relies on downlink cooperation between Base Stations.

Cooperative communications [2] are new techniques to improve wireless networks performances by generating spatial diversity. They consist in transmitting signals from different locations, thus performing virtual Multiple Inputs, Multiple Outputs (MIMO) arrays. Cooperation has been introduced in [3] [4] [5] where some terminals serve as relays for another terminal's transmission. Then Laneman et al. [6] [7] proposed two cooperation transmission protocols, Amplify-and-Forward (AF) and Decode-and-Forward (DF). These protocols are well adapted for uplink transmission with a wireless link between source and relay. Few studies have been performed on downlink cellular cooperation [8] so far, and these studies use the relay for coverage improvement, without diversity.

In this paper, we propose a strategy for downlink cooperation at cell's border. Cooperation is performed between Base Stations, on a channel assumed perfect. Our work focuses on the impact of cooperation on Radio Resource Management algorithms: power control and resource allocation. Indeed, cooperation should not be performed at the expense of inter-cell interference increase and should not induce power limitations. Our RRM algorithm for downlink cooperation is composed of three steps: it first determines the list of users that require relaying, then assign subcarriers on source and relay links, and finally performs power control on source and relay links. Each step is performed independently on each Base Station. Our RRM strategy is consequently suitable for distributed networks. It is also efficient in terms of signaling, as inter-Base Stations' signalling is limited to data forwarding.

The paper is organized as follows. Section II introduces the system model and notations. Section III presents the distributed algorithm for subcarrier allocation and power control. The performances of this algorithm on capacity, Signal to Noise Ratio and inter-cell interference, are gathered in Section IV. Conclusions are given in last section.

II. SYSTEM MODEL

Our model is composed of two rings of interfering Base Stations with omnidirectional antennas with same cell radius. All Base Stations use OFDMA with same FFT size N_{FFT} . We suppose that there are N_{users} users per Base Station. We assume that each user is assigned one sub-carrier by its serving Base Station, and may be relayed by at most one Base Station.

The users of the 7 central Base Stations $(BS_0 \text{ to } BS_7)$ may be relayed in downlink. For each user k of the 7 central Base Stations, the source Base Station will be denoted $BS_{s,k}$. Then, the chosen relaying Base Station, denoted $BS_{r,k}$, will be the neighbouring Base Station that minimizes the path loss to user k.

Transmission between two Base Stations is assumed perfect. A two-time slot relaying scheme is used: at time t, $BS_{s,k}$ transmits symbol $x_{k,1}$ to user k and forwards it to $BS_{r,k}$ for relaying purpose. At time t + 1, $BS_{s,k}$ transmits symbol $x_{k,2}$ to user k, and $BS_{r,k}$ relays symbol $x_{k,1}$ to user k. Let $\vec{y}_k = (y_{k,1}, y_{k,2})$ be the vector of symbols received by user k.

$$y_{k,1} = h_{s,k} \sqrt{\frac{p_{s,k}}{l_{s,k}(\sigma^2 + I_{s,k})}} x_{k,1} + n_{k,1} \tag{1}$$

$$y_{k,2} = h_{r,k} \sqrt{\frac{p_{r,k}}{l_{r,k}(\sigma^2 + I_{r,k})}}} x_{k,1} + h_{s,k} \sqrt{\frac{p_{s,k}}{l_{s,k}(\sigma^2 + I_{s,k})}}} x_{k,2} + n_{k,2}$$
(2)

where

- $p_{s,k}$ (resp. $p_{r,k}$) is the transmit power from the source (resp. the relay) to user k.
- $l_{s,k}$ (resp. $l_{r,k}$) is the path loss (including shadowing) from the source (resp. the relay) to user k.
- $h_{s,k}$ (resp. $h_{r,k}$) is the fast fading channel coefficient between the source (resp. the relay) and the user k.
- $I_{s,k}$ (resp., $I_{r,k}$) is the inter-cell interference received by user k on the subcarrier allocated on its link with $BS_{s,k}$ (resp. $BS_{r,k}$).
- σ^2 is the noise variance, which is the same on both links, as it only depends on the destination (user k). $\vec{n}_k \sim C\mathcal{N}(0, I)$ is AWGN.

Let $f_{s,k}$ (resp. $f_{r,k}$) be the sub-carrier allocated by the source (resp. the relay) Base Station to user k. The interference received by user k on its link with the source Base Station $I_{s,k}$ and on its link with the relay Base Station $I_{r,k}$ are:

$$I_{s,k} = \sum_{i=0|i\neq s}^{N_{BS}} \frac{|h_{i,f_{s,k}}|^2 p_{i,f_{s,k}}}{l_{i,k}}$$
(3)

$$I_{r,k} = \sum_{i=0|i\neq r}^{N_{BS}} \frac{|h_{i,f_{r,k}}|^2 p_{i,f_{r,k}}}{l_{i,k}}$$
(4)

where $N_{BS} = 18$. The transmission channel can be modelled as:

$$\vec{y}_k = \mathbf{H}_k \vec{x}_k + \vec{n}_k. \tag{5}$$

 \mathbf{H}_k is the equivalent channel matrix for user k:

$$\mathbf{H}_{k} = \begin{pmatrix} h_{s,k} \sqrt{\frac{p_{s,k}}{l_{s,k}(\sigma^{2} + I_{s,k})}} & 0\\ h_{r,k} \sqrt{\frac{p_{r,k}}{l_{r,k}(\sigma^{2} + I_{r,k})}} & h_{s,k} \sqrt{\frac{p_{s,k}}{l_{s,k}(\sigma^{2} + I_{s,k})}} \end{pmatrix}$$
(6)

We assume that $E[\vec{x}_k \vec{x}_k^*] = \mathbf{I}$. Then link capacity is [9]:

$$C_{k} = \frac{1}{2} \log_{2} \left(\det(\mathbf{I} + \mathbf{H}_{k} \mathbf{H}_{k}^{*}) \right)$$
(7)
$$= \frac{1}{2} \log_{2} \left(\left(1 + \frac{|h_{s,k}|^{2} p_{s,k}}{l_{s,k}(I_{s,k} + \sigma^{2})} \right)^{2} + \frac{|h_{r,k}|^{2} p_{r,k}}{l_{r,k}(I_{r,k} + \sigma^{2})} \right)$$

III. RADIO RESOURCE MANAGEMENT STRATEGY

In this section, we present an algorithm for downlink cooperation which determines users that require relaying, assigns subcarriers on source and relay links, and performs power control on source and relay links.

A. Cooperation triggering condition

Cooperation between Base Stations may become costly in terms of resource consumptions (subcarrier and power). It should not be performed at the expense of decreasing the capacity of the non relayed users. If a user is relayed by a far Base Station, this Base Station will require a high power value which will generate a high inter-cell interference for users using the same sub-carrier.Consequently, we restrict relaying to cases where users have almost the same path loss value to their source Base Station as to their relay Base Station:

$$(l_{r,k} - l_{s,k})_{dB} \le \Delta \tag{8}$$

B. Subcarrier allocation on relayed and non-relayed links

To simplify the problem, we have made the assumption that each user can use at most one subcarrier per Base Station. Subcarrier allocation is first performed, for each user, on the direct link with its Base Station. We assign the first free subcarrier that maximizes the fast fading channel coefficient $h_{s,k}$. Then for the relayed link, two methods are tested. The first method consists in allocating the first free subcarrier that maximizes $h_{r,k}$. In this case, the user receives inter-cell interference on two different subcarriers. The second method consists in trying to allocate the same subcarrier on the relay link as on the direct link, in order to decrease inter-cell interference. However, relay links cannot pre-empt direct links which have a higher priority. So if the direct link's subcarrier is already allocated, then we fall back to choosing the first free subcarrier with highest channel coefficient.

C. Power control to maximize capacity

Our aim is to maximize the sum capacity on each Base Station, by allocating power values on each subcarrier. The general optimization problem is, for each Base Station indexed by $i \in [0, ..., N_{BS}]$:

maximize
$$_{\vec{p}_i} \left(\sum_{k=1}^{N_{users}} C_k \right)$$

subject to $\vec{1}^T \vec{p}_i = P_{max}$ (9)

More specifically we get two cases.

1) Power control on the the second ring

On the Base Stations where users are not relayed $(BS_7 \text{ to } BS_{18})$, some sub-carriers are dedicated to relaying external users $(N_r \text{ with power vector } \vec{p_r})$, while the other ones are dedicated to internal users $(N_d \text{ with power vector } \vec{p_d})$. In order to ensure that relayed users have sufficient power allocation, we impose that a part of the total power be dedicated to relays. We therefore have $P_{\text{relay}} + P_{\text{direct}} = P_{\text{max}}$ and simulations show that

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the best ratio value is $P_{\text{relay}} = \frac{N_r}{N_r + N_d} P_{\text{max}}$. As power constraints are independent on relay links and on direct links, we can separate the problems.

maximize
$$\vec{p}_{\text{relay}} \left(\sum_{k=1}^{N_r} C_{\text{relay},k} \right)$$

subject to $\vec{1}^T \vec{p}_r = P_{\text{relay}}$ (10)

and

maximize
$$\vec{p}_{direct} \left(\sum_{k=1}^{N_d} C_{direct,k} \right)$$

subject to $\vec{1}^T \vec{p}_d = P_{direct}$ (11)

Both problems are convex optimization problems, which can be solved by using the Karush-Kuhn-Tucker (KKT) conditions [10]. A detailed derivation of this solution can be found in [11]. The optimal solution for relayed users is:

$$p_{r,k} = \left[\frac{1}{\mu_r} - \frac{l_{r,k}(\sigma^2 + I_{r,k})}{|h_{r,k}|^2} \left(1 + \frac{|h_{s,k}|^2 p_{s,k}}{l_{s,k}(\sigma^2 + I_{s,k})}\right)^2\right]^+ (12)$$

where $[x]^+ = \max\{0, x\}$ and $p_{s,k}$ is the power transmitted by their source Base Station. The constant μ_r must be chosen so that the power constraint $\vec{1}^T \vec{p}_r = P_{\text{relay}}$ is fulfilled. The solution for direct users is:

$$p_{d,k} = \left[\frac{1}{\mu_d} - \frac{l_{d,k}(\sigma^2 + I_{d,k})}{|h_{d,k}|^2}\right]^+$$
(13)

where constant μ_d must be chosen so that the power constraint $\vec{1}^T \vec{p}_d = P_{\text{direct}}$ is fulfilled.

2) Power control on the first ring

On the Base Stations where users are relayed (BS_0 to BS_6), some sub-carriers are dedicated to relaying external users, while the other ones are dedicated to internal users, and a part of these users are being relayed by an external Base Station. The same part of the maximal power $P_{\text{relay}} = \frac{N_r}{N_r + N_d} P_{\text{max}}$ is dedicated to relay. The problem can consequently be divided into two separate power allocation problems.

The solution on relayed users \vec{p}_r is given by eq. (12).

For internal users, however, capacity maximization can no longer be solved through direct water-filling as in the second ring case. The problem is now

maximize
$$\vec{p}_{direct} \left(\sum_{k=1}^{N_{d_r}} C_{\text{source},k} + C_{\text{direct},k} \right)$$

subject to $\vec{1}^T \vec{p}_d = P_{\text{direct}}$ (14)

where users denoted source, k are relayed by an external Base Station, and users denoted direct, k are not relayed.

In the case where all users are relayed, then the solution can be obtained analytically with the KKT conditions [11].

$$p_{s,k} = \left[\frac{1}{\mu_s} + \frac{1}{\mu_s}\sqrt{a_k} - \frac{l_{s,k}(\sigma^2 + I_{s,k})}{|h_{s,k}|^2}\right]^+$$
(15)

where

$$a_{k} = \left[1 - \frac{\frac{p_{r,k}|h_{r,k}|^{2}}{l_{r,k}(\sigma^{2} + I_{r,k})}}{(\frac{|h_{s,k}|^{2}}{l_{s,k}(\sigma^{2} + I_{s,k})})^{2}}\mu_{s}^{2}\right]^{+}$$

and μ_s is a constant parameter that must be chosen in order to fulfill the power constraint $\vec{1}^T \vec{p}_d = P_d$.

In the general case, we have solve the global problem on \vec{p}_d numerically with Newton method under equality constraints [10].

Remark: The whole algorithm can be performed in a distributed way by iterating the optimization process on all Base Stations. It should also be noticed that our power control method enables power to be set to 0 on some sub-carriers. Therefore, our method can also be seen as an admission control method: when the Signal to Noise Ratio of a link is too low, no power is allocated on this link. As we always try to allocate the best possible channel, this implies that some user cannot be served. Our method is consequently not fair if we focus on the instantaneous behaviour of the network (which is the case in our snap-shot based simulations). The dynamic behaviour should be studied, in order to evaluate the actual dropping probability.

IV. PERFORMANCE

This section presents the performances of our RRM algorithm for downlink cooperation, and evaluates the parameters' influence. Performances are assessed with Monte-Carlo simulations, with $N_{\rm FFT} = 256$ and $N_{\rm users} = [32, ..., 224]$. Our model has been described in II. Simulation's parameters are

- Inter-site distance is $d_{is} = 0.7\sqrt{3} = 1.212$ km.
- The path loss model is Okumura-Hata [12]: $l(d) = 137.74 + 35.22 \log(d)$ in dB.
- Shadowing's standard deviation is 7 dB.
- The downlink noise is $\sigma^2 = -105 \text{ dBm}$.
- The maximum transmit power for each base station is $P_{\text{max}} = 43 \text{ dBm}.$

The number of iterations is set so as to achieve convergence for most power values. It depends on the inter-cell interference level, and consequently on the load. In the following, the performance results are averaged over BS_0 in order to avoid side effects.

In sections A and B, we set $\Delta = 3$ dB and use the first subcarrier allocation method. Then sections C and D evaluate the influence of Δ and of the subcarrier allocation method.

Remark: The performance results of our cooperation scheme are compared with a non-relaying power control method in which power values are allocated on each Base Station in order to maximize the sum capacity

$$\sum_{k=1}^{N_{users}} \left(\log_2 \left(1 + \frac{|h_{s,k}|^2}{l_{s,k}(\sigma^2 + I_{s,k})} p_{s,k} \right) \right)$$
(16)

The solution is obtained with water-filling:

$$p_{s,k} = \left[\frac{1}{\mu_s} - \frac{l_{s,k}(\sigma^2 + I_{s,k})}{|h_{s,k}|^2}\right]^+$$
(17)

where μ_s must be chosen so that $\vec{1}^T \vec{p}_s = P_{\text{max}}$.

A. Performance improvement

The average link capacity is shown on Fig. 1. Using relay enables to increase the average link capacity at any load, by 10 to 14.5 %. At low to medium load, relaying brings additional power, while inter-cell interference's influence (corresponding to an increase of 18 dB) is mitigated by power control, which leads to capacity improvement. At high load, two limitations occur: first, the relays also become power-limited, second, some of the users that request relaying cannot be relayed, because there are no free subcarriers on their candidate relay Base Station.

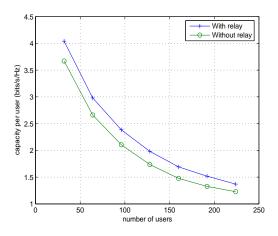


Figure 1: Influence of load on average user capacity

Fig. 2 represents the Cumulative Density Functions (CDF) of the Signal to Interference Ratio (SIR) -including noise- on all users, for different loads. Relaying globally increases the SIR of all users. The gain is more important at high load, when more users are likely to be rejected from their source Base Station because of the total power constraint. Indeed, our power control method (with and without relay) does not allocate any power to users whose power requirements are too high. Therefore, it performs admission control and does not serve users in too bad radio conditions. Fig. 2 shows that the proportion of users with very low SIR decreases thanks to relay.

On Table 1, we have gathered the rejection probability if a user is disconnected with SIR ≤ -10 dB. It is 2.4 times lower if $N_{\text{users}} = 32$, and 1.5 times lower if $N_{\text{users}} = 224$.

Consequently, even if our cooperation algorithm brings a limited improvement in average link capacity, it is especially efficient for users that would be rejected if relaying was not used. It is therefore particularly adapted for improving the SIR of users located at cell border, and reducing Quality of Service discontinuities for users that perform a handover between two

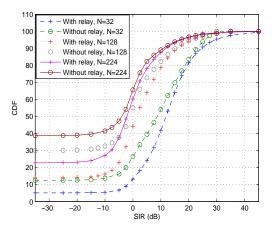


Figure 2: CDF of Signal to Interference Ratio, N=32, 128 and 224

cells. Although these results are already interesting, it should be noted that they could be improved by allocating more subcarriers to each user, and by using a dynamic scheduling that would take the service into account.

1	$N_{\rm users}$	Without relay	With relay
	32	13.75	5.53
	64	22.23	9.98
	96	28.23	12.71
	128	32.63	16.22
	160	36.13	19.23
	192	39.08	22.66
	224	41.50	27.02

Table 1: Rejection probability for $SIR_{min} = -10 \text{ dB}$

B. Resource consumption for relayed users

Cooperation between Base Stations requires additional power and subcarrier resources. In our power control scheme, we have dedicated power ratio $P_{\text{relay}} = \frac{N_r}{N_r + N_d} P_{\text{max}}$ to relayed users. The number of relayed users N_r is determined thanks to the cooperation triggering condition on path loss. However, users requesting relaying are not necessarily allocated a subcarrier and power on the relay link: subcarrier allocation depends on the load, as relayed users have lower priority than direct users for resource allocation, and power allocation depends on the power control mechanism.

Table 2: Resource consumption

Nusers	% active relaying	% power allocated to relay		
≤ 160	25	36		
192	25	25		
224	12.5	12.5		

Table 2 shows that at low to medium load, the percentage of active relaying remains lower than the ratio of requested relaying. Power control does not provide any relay power. This confirms the fact that our power control method is not fair. It is a "greedy" power control scheme, similar to water-filling, since the cost to maximize is sum capacity and not the number of active relayed users.

C. Influence of cooperation triggering parameter

The influence of the cooperation triggering parameter Δ is evaluated for $N_{\text{users}} = 32$. The results are summarized in Table 3. We can see that the capacity increase of relayed users is balanced by the capacity decrease of non-relayed users, as the additional power dedicated to relayed links is obtained at the expense of the power of direct links.

To conclude, setting $\Delta = 3$ dB is more efficient, because a higher value takes power from the base Station's direct users without providing any significant capacity gain.

Table 3: Influence of cooperation triggering parameter

Δ (dB)	3	6	12
% of requested relay	46	56.4	74.4
link capacity (b/s/Hz)	4.04	4.06	4.07
$P_{\text{relay}}(\mathbf{W})$	7.1	8.3	10.1

D. Influence of subcarrier allocation method

In this section, we compare the two subcarrier allocation methods for the relay link that are described in section III.B. The average link capacity with both methods and without relaying is presented on Fig. 3.

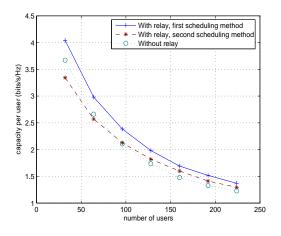


Figure 3: Comparison of resource allocation methods

The second subcarrier allocation method is not efficient because the chosen subcarrier likely corresponds to a bad channel coefficient. In that case, the requested transmit power on the relay link is too high, which leads to inefficient power allocation. This loss is not made up for by the inter-cell interference decrease. At low load, the second resource allocation method performs even worse than if there were no relaying, because the power ratio which is dedicated to relaying is inefficiently used, and would better be allocated to direct users. As the load increases, the probability that the subcarrier used on the direct link be free decreases, and more users eventually use the first subcarrier allocation method (*i.e*, choose the best h), which explains the capacity increase. To conclude, subcarrier allocation should be opportunistic in order to maximize the capacity, as the influence of inter-cell interference can be efficiently mitigated by power control.

V. CONCLUSIONS

In this paper, we have proposed a resource allocation and power control algorithm for cooperation between distributed Base Stations. Power control is performed iteratively on the different Base Stations in order to mitigate the influence of inter-cell interference. Our algorithm leads to capacity increase at any the load value, which is achieved in spite of the inter-cell interference increase. It is especially efficient for decreasing the rejection probability. Besides, it should be triggered only at cell's border in order to decrease the consumption of power dedicated to relay and should make use of opportunistic transmission as much as possible in order to increase capacity.

Cooperation between Base Stations is consequently a very promising technique for mobility in future distributed cellular networks: indeed, it enables a smooth transition from one cell to the other, while beeing less costly in terms of infrastructure and network management than macrodiversity.

Future work will consist in defining new scheduling methods, based on new cooperation protocols, that will bring fairness to users and will be adapted to different Quality of Service's constraints.

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