COOPERATIVE TRANSMISSION FOR WIRELESS NETWORKS USING POWER CONTROL AND BEAMFORMING

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ABSTRACT

One of the most promising techniques to increase wireless system capacity is the use of multiple antennas in transmission and reception. When multiple antennas are available only at the base station, the advanced processing algorithms for achieving high data rates in downlink must be supported almost exclusively by the transmitter. Spatial Division Multiple Access (SDMA) schemes have been widely used for this task, and its application together with power control for CDMA networks has obtained good results in order to increase system capacity. In this paper an extended algorithm using beamforming and power control, but allowing for cooperative transmission from all base stations to each active mobile is presented. Main advantages of this extension are discussed and some simulation results are presented.

1. INTRODUCTION

Over the last few years, the increase in the number of mobile subscribers coupled with the emergence of new bandwidth consuming services, stress the necessity for new methods with the ability to exploit more effectively the scarce spectrum available. Wideband Direct Sequence Code Division Multiple Access (DS-CDMA) has been adopted as a radio access technology for third generation mobile communication systems due to its ability to provide a high system capacity and its flexibility to support a variety of voice and data services with diverse Quality of Service (QoS) requirements.

One of the trade-offs of high capacity in CDMA networks is the increasing of interference power over the network. Thus power control techniques are considered of mandatory use in this kind of systems. On the other hand, one of the most promising techniques to increase wireless system capacity is the use of multiple antennas at transmission and reception [1]. In order to achieve as high transmission rates as expected, efficient algorithms that could make use of Spatial Division Multiple Access (SDMA) [2, 3, 4] and/or space-time coding [5] are being payed lot of attention by the researching community.

One of the most interesting algorithms that makes use of SDMA and power control to increase system capacity is that proposed by Rashid-Farrokhi *et al* in [4] for TDD networks. In [6] a new reformulation of this algorithm for DS-CDMA systems has been proposed, and promising results using an optimum base station assignment [6, 7] have been obtained. However one of the main drawbacks of this algorithm is the need of a centralized control power for all the cells involved. Nevertheless, for a limited number of base stations this technique could be efficiently used.

In this paper, on one hand an extended version of the aforementioned algorithm [4, 6] including cooperative transmission from all the base stations to each mobile is presented. On the other hand the concept of involving several cells has been changed to one unique cell (node B in UMTS) but with several antenna sites (Base Stations) distributed over the coverage area and connected to the node B processing core by means of Radio-over-fibre technology (see figure 1).

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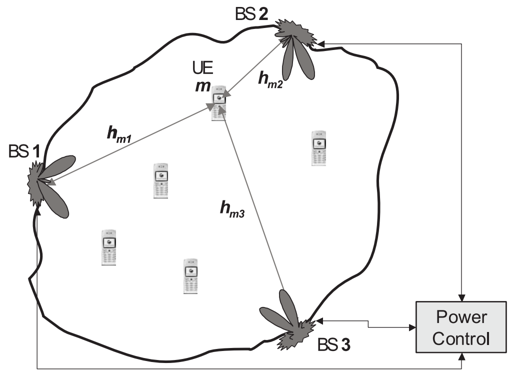

Figure 1: Example of a single cell with 3 distributed sites of antennas controlled by a central processing unit.

From the SDMA algorithm point of view, the main difference between network configurations as in [2, 3] and this one is that same scrambling code is used by all the BS's. However from the network planning point of view, improvements in resource management due to simple reconfiguration should be provided. Examples of this kind of *distributed node B* might be several micro-cells serving in cooperation with a macro-cell, or a macro-cell covering non-conventional shape areas as tunnels, malls with hot spots, etc.

Paper is organized as follows: Section 2 sets up the model and notation, section 3 develops the proposed algorithm and discusses its practical aspects, section 4 shows some simulation results and section 5 summarizes relevant conclusions.

2. MODEL AND NOTATION

A system with several base stations serving a single cell in a CDMA system is considered as in figure 1. Each base station is equipped with an array of P antennas and the power control is carried out by a Central Processing Unit. We call K the number of base stations and M the number of co-channel users, so the suffix mk represents the link between mobile m and base station k.

FDD uplink and downlink radio transmission have to be modelled with different resulting attenuation from Rayleigh fading, whereas shadowing and space free loss effects are similar. Nevertheless both uplink and downlink channels have similar second-order statistics in flat fading scenarios, and we suppose that some kind of feedback takes place between mobile and BS in order to estimate the downlink channel response. In [10] there is a very interesting approach to the herein proposed algorithm performance when perfect knowledge of downlink channel responses is not available.

In the model herein presented all the multipaths that contribute to the Rayleigh fading are supposed to arrive not later than a chip period (flat fading). Under these assumptions, the signal received at mobile m at time t from all the base stations, is given by:

$$r_m(t) = \sum_{k=1}^{K} \mathbf{h}_{mk}^H \mathbf{x}_k(t) + \tilde{n}_m(t), \quad (1)$$

where $\mathbf{h}_{mk}^H$ models the $[P \times 1]$ downlink channel gain between BS k and mobile m with $(\cdot)^H$ representing the conjugated transposed, $\tilde{n}_m(t)$ includes the thermal noise and the multiple access interference (MAI), and $\mathbf{x}_k(t)$ is the signal transmitted by BS k, which will have the form:

$$\mathbf{x}_k(t) = \sum_{i=1}^{M} \mathbf{w}_{ik} \sqrt{P_{ik}} s_i(t). \quad (2)$$

In (2) $\mathbf{w}_{ik}$ stands for the downlink beamformer of BS k designed to transmit the CDMA signal $s_i(t)$ to mobile i with power P_{ik}, therefore considering that $s_i(t)$ has unit power. Note that it is not necessary to assume that BS k has been assigned to serve mobile i, because all the Base Stations cooperate to transmit the same signal $s_i(t)$ to mobile i.

To distinguish in (1) the term of interest from the interferences after the despreading process, the resulting baseband signal can be separated into the following terms:

$$\begin{aligned} r_m(t) &= \sum_{k=1}^{K} \mathbf{h}_{mk}^H \mathbf{w}_{mk} \sqrt{P_{mk}} s_m(t) \\ &+ \sum_{k=1}^{K} \sum_{i=1, i\neq m}^{M} \mathbf{h}_{mk}^H \mathbf{w}_{ik} \sqrt{P_{ik}} s_i(t) + n_m(t), \end{aligned} \quad (3)$$

where the first term represents the signal of interest, the second term the co-channel interference and the third one the reduced thermal noise and MAI.

3. POWER CONTROL AND BEAMFORMING IN COOPERATIVE TRANSMISSION

The algorithm presented hereafter is based in classical methods of designing suboptimal transmission beamformers [4, 2] and achieving to transmit minimum power over the network by means of power control. Together with these objectives, a certain QoS represented by signal to noise and interference ratio (SINR) must also be assured for all the active mobiles. On the other hand the algorithm presents a new interesting feature, since it allows for cooperative transmission between all the BS and each mobile, in such a way that no previous BS assignment has to be carried out or internal handover has to be expected. The cooperative transmission algorithm can be summarized in two main actions: calculate transmitting beamformers, and update downlink power transmission in order to achieve the required SINR (QoS).

3.1 Beamformer Calculation

To calculate optimal beamformer for user m, the respective signal to noise and interference ratio SINR from (3) must be maximized:

$$\text{SINR}_m = \frac{\sum_{k=1}^{K} P_{mk} \mathbf{w}_{mk}^H \mathbf{H}_{mk} \mathbf{w}_{mk}}{\sum_{k=1}^{K} \sum_{i=1, i\neq m}^{M} P_{ik} \mathbf{w}_{ik}^H \mathbf{H}_{mk} \mathbf{w}_{ik} + \sigma_m^2}, \quad (4)$$

where matrix $\mathbf{H}_{mk} = E[\mathbf{h}_{mk}\mathbf{h}_{mk}^H]$ is the second-order statistics of channel mk and $\sigma_m^2 = E[n_m n_m^*]$ represents the noise and MAI power. In (4) it has been assumed that channel gains $\mathbf{h}_{mk}$ and $\mathbf{h}_{ml}$ are uncorrelated for $k \neq l$ due to the large separation between base stations around the cell. Likewise uncorrelation between signals $s_i(t)$ and $s_m(t)$ has been considered.

The solution of (4) involves a search over the entire set of beamformers $\mathbf{w}_{ik}$ that is not feasible. However, if we consider the problem of joint computation of a viable set of weight vectors $\mathbf{w}_{ik}$ and power allocations P_{ik}, the algorithm proposed in [4] achieves the optimal solution (in the minimum total transmitted power sense) provided that there exists at least one feasible solution. This algorithm makes use of a *virtual uplink* network whose channel responses are similar to those of the respective downlinks. Due to this approach, the received SINR at BS k for desired mobile m can be expressed as:

$$\text{SINR}_{mk}^{vu} = \frac{\rho_{mk} \mathbf{w}_{mk}^H \mathbf{H}_{mk} \mathbf{w}_{mk}}{\mathbf{w}_{mk}^H \left[\sum_{i=1, i\neq m}^{M} \rho_{ik} \mathbf{H}_{ik} + \mathbf{I}\right] \mathbf{w}_{mk}}, \quad (5)$$

where ρ_{ik} are the virtual uplink transmission powers that must be updated as real powers P_{ik} do. Consequently the beamformers $\mathbf{w}_{mk}$ will be designed to maximize expression (5), not (4).

3.2 Power Updating

Downlink power updating intends to minimize the total transmission power but assuring that a minimum SINR is reached at each mobile. In this sense, once the set of beamformers is fixed, minimum power will be met when all the mobiles receive their signals with the minimum SINR required, i.e., when the following equality is given for all m:

$$\text{SINR}_m = \gamma_m , \quad (6)$$

being γ_m the SINR target for user m, and SINR_m expressed as in equation (4).

In order to update all the transmission powers in a single step, a new formulation of the associated indices of powers, beamformers and channel matrices is required.

Without loss of generality we begin by the first BS, $k = 1$, to setup the new indices: as BS 1 is transmitting to all the mobiles in a cooperative way, its M transmission powers P_{i1} are involved in the updating process. From now on, those M powers are renamed as $P_{i1} \rightarrow P_j, j = 1, \ldots, M$. In the same way, there will be also M powers of BS 2 that will be renamed as $P_{i2} \rightarrow P_j$, with $j = M+1, \ldots, 2M$. Generalizing, given BS k and mobile i, new parameter indices will be expressed as:

$$\left.\begin{array}{r} P_{ik} \rightarrow P_j \\ \rho_{ik} \rightarrow \rho_j \\ \mathbf{H}_{ik} \rightarrow \mathbf{H}_j \\ \mathbf{w}_{ik} \rightarrow \mathbf{w}_j \end{array}\right\} j = (k-1)M + i.$$

With this new notation, SINR equality (6) for user m takes the following simple form:

$$\sum_j P_j \mathbf{w}_j^H \mathbf{H}_j \mathbf{w}_j = \gamma_m \sum_n P_n \mathbf{w}_n^H \mathbf{H}_j \mathbf{w}_n + \gamma_m \sigma_m^2, \quad (7)$$

where subscript j is such that $j = (k-1)M + m$ for $k = 1, \ldots, K$, whereas subscript n follows $n = (k-1)M + i$ for $k = 1, \ldots, K; i = 1, \ldots, M$ and $i \neq m$, as in (6).

If transmission power vector $\mathbf{p}$ of length KM is defined as:

$$\mathbf{p} = [\underbrace{P_1, \ldots, P_M}_{\in \text{BS}_1}, \ldots, \underbrace{P_{(K-1)M+1}, \ldots, P_{KM}}_{\in \text{BS}_K}]^T,$$

where $[\cdot]^T$ stands for transposed, power updating equation (7) can be rewritten in matrix form as:

$$\mathbf{D}\mathbf{p} = \mathbf{F}\mathbf{p} + \mathbf{u}. \quad (8)$$

In the above expression, matrix $\mathbf{D}$ is $[M \times KM]$ and presents a particular partition of K diagonal matrices $\mathbf{D}_k$ of dimensions $[M \times M]$ with respective non-zero elements given by:

$$\mathbf{D} = [\ \mathbf{D}_1 \mid \mathbf{D}_2 \mid \cdots \mid \mathbf{D}_K\ ] \quad (9)$$

$$[\mathbf{D}_k]_{mm} = \mathbf{w}_j^H \mathbf{H}_j \mathbf{w}_j, \quad (10)$$

where index j is related to k and m by means of $j=(k-1)M+m$.

In the same way, matrix $\mathbf{F}$ has dimensions $[M \times KM]$ and presents a particular partition of K matrices $\mathbf{F}_k$ of dimensions $[M \times M]$ as:

$$\begin{aligned} \mathbf{F} &= [\ \mathbf{F}_1 \mid \mathbf{F}_2 \mid \cdots \mid \mathbf{F}_K\ ] \\ [\mathbf{F}_k]_{mi} &= \begin{cases} \gamma_m \mathbf{w}_n^H \mathbf{H}_j \mathbf{w}_n & ,m \neq i \\ 0 & ,m = i \end{cases}, \end{aligned}$$

where index j is related to indices k and m as $j=(k-1)M+m$, whereas index n is related to indices k and i by means of $n=(k-1)M+i$, provided that $m \neq i$.

Finally, vector $\mathbf{u}$ is defined as:

$$\mathbf{u} = \left[\gamma_1 \sigma_1^2, \ldots, \gamma_M \sigma_M^2\right]^T.$$

Returning to power update equation (8), this could be directly solved if final beamformers had been previously designed, or recursively solved if beamformers also had to be recalculated in each iteration. In this last case, the min-norm solution is given through the Singular Value Decomposition (SVD) of matrix $\mathbf{D}$ (assuming that it is full-rank):

$$\mathbf{D} = \sum_{m=1}^{M} \lambda_m \mathbf{b}_m \mathbf{c}_m^H$$

and the recursive equation to update transmission powers will be [8]:

$$\mathbf{p}(N_{it}+1) = \sum_{m=1}^{M} \frac{1}{\lambda_m} \mathbf{b}_m^H (\mathbf{F}\mathbf{p}(N_{it}) + \mathbf{u}) \mathbf{c}_m, \qquad (11)$$

where N_{it} represents the iteration number. It must be noted that particular sparse structure of $\mathbf{D}$ showed in (9)-(10) allows to minimize the computational cost involved when SVD of such an $[M \times KM]$ matrix is performed.

3.3 Cooperative Transmission Algorithm

To summarize all the above equations in a simple iterative algorithm for control power and beamforming in a cooperative environment of distributed antenna arrays, the following steps are given (assume K base stations and M mobile users, and consider N_{it} as the iteration number):

1. In $N_{it}=0$: Initialize $\rho_n(0)$ and $P_n(0)$ for $n=1,\ldots,KM$ with positive values.

2. For $N_{it}=1,2,\ldots$ until convergence do:

Beamforming Calculate the suboptimal transmit beamformers $\mathbf{w}_j$ for each link $j=1,\ldots,KM$ as:

$$\mathbf{w}_j = \arg\max_{\mathbf{w}_j} \frac{\rho_j \mathbf{w}_j^H \mathbf{H}_j \mathbf{w}_j}{\mathbf{w}_j^H \left[\sum_n \rho_n \mathbf{H}_n + \mathbf{I}\right] \mathbf{w}_j}, \qquad (12)$$

where index n is taken over $M-1$ values related to j as follows: provided that $j=(k-1)M+m$, then n takes the form $n=(k-1)M+i$ being $i=1,\ldots,M$ and $i \neq m$. That is, from the point of view of virtual uplink, the interferers of the j link are the remaining $M-1$ links associated to the same base station k.

Power Control Update the transmitted power vector $\mathbf{p}$ using (11).

Virtual Uplink Update parameter ρ_j for each link $j=1,\ldots,KM$ by means of classical distributed power control [9]:

$$\rho_j(N_{it}+1) = \frac{\gamma_m}{\mathrm{SINR}_j^{vu}(t)} \rho_j(N_{it}), \qquad (13)$$

where SINR_j^{vu} is the virtual uplink SINR given by (5):

$$\mathrm{SINR}_j^{vu} = \frac{\rho_j \mathbf{w}_j^H \mathbf{H}_j \mathbf{w}_j}{\mathbf{w}_j^H \left[\sum_n \rho_n \mathbf{H}_n + \mathbf{I}\right] \mathbf{w}_j},$$

with indices j and n described as in equation (12).

3.4 Practical Aspects of Cooperative Transmission

Some practical aspects of the cooperative transmission must be outlined in comparison with single base station transmission:

1. Cooperative transmission does not need previous base station assignment, so handovers inside the cell are avoided. Comparing to the algorithm proposed in [7] that uses an optimal base assignment procedure that involves a searching over all the SINR values of the virtual uplink, system complexity is drastically reduced.

2. As all the base stations are transmitting to all the mobiles, the total network power is increased with respect to the one BS case. Moreover, cooperative transmission may be harmful in some situations: when a mobile has a deep fading in one of their links, the concerned BS must spend a lot of power trying to achieve the target SINR, and consequently interference power to other mobiles will be increased. To avoid this situation, a variation of the cooperative transmission algorithm is proposed: Not all the BS cooperate to transmit information to every mobile, but only those that belong to the mobile *active set*.

This particular *active set* is generated in a similar way as soft handover procedures do: The mobile station continuously monitors the received power of the pilot channel transmitted by all the BS. Then the received pilot power levels are compared to a variable threshold, whose value is given by the maximum of the pilot powers minus a certain margin, M_g, in dB. As a result of this comparison, the active set of cooperative BS for that mobile is formed by all the BS whose pilot signal strength is above the threshold, or, in other words, whose pilot signal level falls into the window of width M_g dB placed below the maximum of the pilot powers.

It must also be noted that although the threshold is dynamically adjusted by each mobile, the margin value can be previously set up by the network depending on resource management criteria of higher layers.

3. Last advantage of the cooperative transmission is the reconfiguration capacity that it exhibits. For example, when low traffic load is being supported, each mobile can be served by a single BS. But in hot spots, collaboration between several base stations may be considered as a positive solution. In this case, the cooperative transmission algorithm can be automatically adapted to the new situation with only changing the margin value M_g.

4. SIMULATIONS

The simulation environment consists of 3 base stations distributed around a single cell. Each base station is equipped with an array of 4 antennas separated half the wavelength. Channel responses from all mobiles to all BS are known, and Rayleigh fading has been generated by 3 paths with average gain of 0 dB and angular spread of 120°. In order to simulate a realistic scenario, constraint in power levels has also been imposed: each BS has a limit in transmission power of 43 dBm.

DS-CDMA signals with a spreading factor of 16 have been used, but from notation showed in Sections 2 and 3, only the associated signal powers are necessary to evaluate the algorithm. However, a MAI (after despreading) of 10 dBm has been considered in the power update step for each mobile.

In each simulation, system begins with one user and tries to incorporate as many users as possible provided that all mobiles maintain an SINR target (equivalent to QoS) in downlink. The distribution of the initial mobile position inside the cell is uniform, but a user velocity of 4 km/h is considered. For evaluating the behavior of the algorithm the average number of co-channel users admitted in

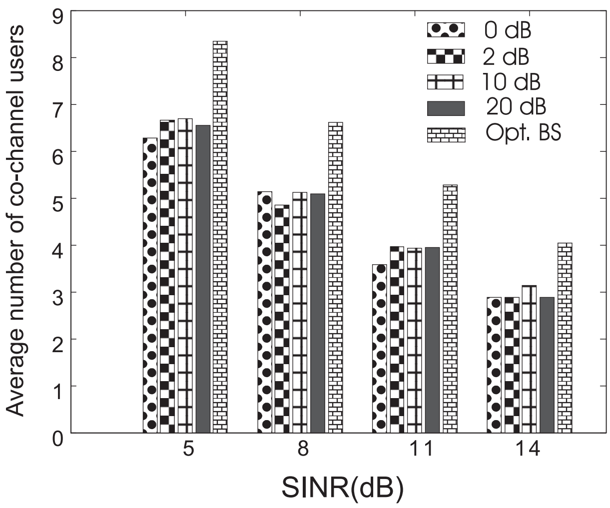

Figure 2: Average number of co-channel users admitted by the cooperative transmission algorithm versus required SINR. Different values of the margin M_g used to compose the active set are also compared to the optimum BS assignment method of [7].

Margin (dB)	BS's in the active set
0	1
2	1.14
10	1.7
20	2.2

Table 1: Average number of BS in the active set for the four different margin values used in the simulation.

the cell given a target SINR has been chosen. In order to ensure the confidence of the results, 200 replications of each simulation have been carried out.

Figure 2 shows the average number of users admitted by the cooperative transmission algorithm versus required SINR for different levels of the margin M_g used to compose the active set. This parameter is set up by the network and has the same value for all the mobiles in the cell. In the figure is also compared the average number of co-channel users when optimal base assignment [7] is used.

It can be appreciated that all the configurations of the cooperative transmission algorithm have similar behaviour, although a window of 10 dB seems to slightly outperform the other three. This result appears in contradiction with the idea that more active BS more interference power in the network, so worst behaviour would be expected for 10 dB margin than for 2 or 0 dB. Note that 0 dB represents the usual single BS assignment algorithm, so handover decisions must be considered in this case. Just for comparison, the average number of BS in a mobile active set for the four different window values are given in table 1.

Finally, returning to figure 2 the optimal BS assignment method outperforms cooperative transmission for all the SINRs as it would be expected, but at more complexity expense.

5. CONCLUSIONS

A new algorithm using beamforming and power control, but allowing for cooperative transmission from all base stations to each active mobile has been presented. A practical implementation is also developed in order to prevent the network collapsing in deep fading situations. Main advantage of this new method is the avoidance of handovers between BS involved and the capacity of self-configuration by means of a variable threshold value. Simulation results have shown that 1) cooperative transmission performs as well as usual single BS transmission but without consuming network resources, and 2) in comparison with optimal single BS assignment, cooperative transmission exhibits a bit lower capacity, but reducing favourably the complexity associated to the optimal method.

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