Joint Transmitter Receiver Diversity for Efficient Space Division Multiaccess

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***Abstract*—Beamforming problem is studied in wireless networks where both transmitters and receivers have linear adaptive antenna arrays. Algorithms are proposed that find antenna array weight vectors at both transmitters and receivers as well as the transmitter powers with one of the following two objectives: 1) to maximize the minimum signal-to-interference-and-noise ratio (SINR) over all receivers and 2) to minimize the sum of the total transmitted power satisfying the SINR requirements at all links. Numerical study is performed to compare the network capacity and the power consumption among systems having different number of antenna array elements in a code division multiple access network.**

***Index Terms*—Adaptive antenna arrays, adaptive beamforming, joint transmit and receive beamforming, power control.**

I. Introduction

THE ANTENNA diversity combining has been studied as a means to increase the capacity of wireless communication networks [4]. A receiver antenna array with properly assigned weights is known to form an antenna beam pattern that suppresses the antenna gain toward the directions of the interferers while keeping a constant gain toward its desired signal. The minimum variance distortionless response (MVDR) beamformer is known to be able to minimize the sum of noise and interference by adjusting array weights properly. Receiver beamforming can be implemented independently at each receiver without affecting the performance of the other links. Transmitter antenna array can also help reduce the cochannel interference. However, transmit beamforming affects the interference at all other receivers at different locations. Therefore, the beamformer calculation cannot be done independently at each link [9], [11].

The systems considered so far assumed to have antenna arrays only at one end of the communication links, i.e., either at the receivers [8], [10] or at the transmitters [9], [11]. In those works, because of practical implementations, it was assumed that the antenna arrays are used only at the base stations and omnidirectional antennas are used at the mobiles. In the uplink, the receiver beamforming vectors at the base stations and mobile transmitted power are jointly optimized to minimize the mobile transmitted power such that the signal-to-interference-and-noise ratio (SINR) at each receiver is above a target SINR [8], [10]. It has been shown that there is a unique set of power allocation and receiver beamforming vectors such that the transmitted power is minimized for each mobile. Note that the minimization is achieved not only for the sum of transmit powers, but also for each mobile, i.e., there is a Pareto optimal solution to the joint receiver beamforming and power control problem. In the downlink, the base station transmitted power and transmit beamforming vectors are determined such that the SINR at the mobiles are set to a threshold [9], [11]. It has been shown that in the transmitter diversity problem, there is no solution that minimizes the transmitted power for each link. However, the virtual uplink concept is used to calculate the transmitter beamforming vectors, which minimizes the sum of the transmitted powers [11]. Downlink transmitter beamforming is also found in [6], where the spatial covariance of the received reverse link signal vector is used for calculating the transmitter beamforming weights. In [7], transmit and receive diversity problem is investigated, where only base stations are equipped with antenna arrays. In that work, the mobile transmit powers and the receiver beamforming vectors for uplink and the base station transmit powers and the transmit beamforming vectors for downlink are optimized to minimize the transmit power for a target SINR. It also extended the previous works by introducing multitap equalization for multipath fading channels.

In this paper, we consider a more general case of a system where both mobiles and base stations have transmitter and receiver antenna arrays. The uplink case will be considered for the clarity of the presentation, but the results apply in both directions. In the uplink, we would like to optimize on three sets of variables: the mobile transmitted powers, the mobile transmitter beamforming vectors, and the base station receiver beamforming vectors. Our approach is along the lines of [8]–[11], i.e., the virtual downlink concept is used, whereas in [5], a similar setting is studied but they simply use receiver beamforming vectors for transmission. We propose algorithms to solve two problems: 1) to maximize the minimum SINR over all receivers and 2) to minimize the sum of the total transmitted powers while satisfying the SINR requirements.

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The paper is organized as follows. In Section II, power control with omnidirectional antennas only and previous works on receive-only diversity and transmit-only diversity problems are presented as a background. In Section III, the system model with both transmitter and receiver diversity is described and the joint beamforming and power control problems are formulated. In Section IV, algorithms are proposed that try to solve the above problems. In Section V, simulation results are presented.

II. Background

In this section, first we present the distributed power control algorithm for networks with omnidirectional antennas. Then, we describe algorithms for receiver-only diversity and transmit-only diversity for a network where adaptive arrays are used only at the base stations.

In a network of cochannel links consisting of M mobiles and their base stations, we denote the link gain between the ith mobile and jth base station by G_{ij}. Consider the uplink scenario where both the base station and the mobile are using omnidirectional antennas. Denote the ith mobile transmitted power by P_i. The SINR at the ith receiver (base station) is given by

$$\Gamma_i = \frac{P_i G_{ii}}{\sum_{j \neq i} P_j G_{ji} + N_i} \tag{1}$$

where N_i is the thermal noise at the ith base station. A connection is acceptable if the SINR is no less than the minimum protection ratio γ_0. In an optimal power allocation, the transmitted powers are set to the minimum required level such that the SINR is equal to the link protection ratio. That is,

$$\Gamma_i = \gamma_0, \quad (i = 1, \ldots, M). \tag{2}$$

Combining (1) and (2), we express the link constraint in a matrix form [14], which is actually the optimal power allocation

$$\hat{\mathbf{P}} = (\mathbf{I} - \gamma_0 \mathbf{D}\mathbf{F})^{-1}\mathbf{u} \tag{3}$$

where $\mathbf{D}$ is a diagonal matrix with $[\mathbf{D}]_{ii} = 1/G_{ii}$ and $[\mathbf{F}]_{ij} = G_{ji}$, if $i \neq j$ and $[\mathbf{F}]_{ii} = 0$, and $[\mathbf{u}]_i = \gamma_0 N_i / G_{ii}$. Distributed algorithms have been proposed to achieve the above solution with only local measurements [1], [13]. In these algorithms, the transmitted power is updated iteratively. The power update at the nth iteration is given by

$$\mathbf{P}^{(n+1)} = \gamma_0 \mathbf{D}\mathbf{F}\mathbf{P}^{(n)} + \mathbf{u}. \tag{4}$$

The ith mobile power is updated by

$$P_i^{(n+1)} = \frac{\gamma_0}{G_{ii}} \left(\sum_{j \neq i} P_j^{(n)} G_{ji} + N_i \right). \tag{5}$$

The right-hand side of the above equation is a function of the interference at the ith base station (the quantity inside the parenthesis), the link gain G_{ii}, and the target SINR γ_0. That is, the mobile power can be updated by using only local interference measurements at the ith base station. The power update (5) can also be written as

$$P_i^{(n+1)} = \frac{\gamma_0}{\Gamma_i} P_i^{(n)}. \tag{6}$$

This equation shows that the power update can be done by scaling the current power level by the ratio between the target SINR and the current SINR.

Now we assume antenna arrays with K elements are used only at base stations. First, we consider the receive diversity problem jointly with power control in the uplink. Define

$$\mathbf{v}(\theta) = \left[v^1(\theta), \ldots, v^K(\theta) \right]^T$$

as the array response for the signal coming from direction θ, where $v^k(\theta)$ is the kth array response at direction θ. We assume the slow fading channel. The received signal vector at the ith base station is given by

$$\mathbf{x}_i(t) = \sum_{m=1}^{M} \sqrt{P_m G_{mi}} \sum_{l=1}^{L} a_{mi}^l \mathbf{v}_{mi}(\theta_l) s_m\left(t - \tau_{mi}^l\right) + \mathbf{n}_i(t)$$

where τ_{mi}^l and a_{mi}^l are the lth path delay and fading, respectively. $s_m(t)$ is a message signal transmitted by the mth mobile at time t and $\mathbf{n}_i$ is the thermal noise vector at the input of antenna. If the delay spread from different paths is negligible, we can rewrite the received signal as

$$\mathbf{x}_i(t) = \sum_{m=1}^{M} \sqrt{P_m G_{mi}} \mathbf{a}_{mi} s_m(t - \tau_{mi}) + \mathbf{n}_i(t)$$

where $\mathbf{a}_{mi}$ is defined as the spatial signature of the mth user at the ith base station

$$\mathbf{a}_{mi} = \sum_{l=1}^{L} a_{mi}^l \mathbf{v}_{mi}^l.$$

The output of beamformer is a weighted combination of its inputs $y_i = \mathbf{w}_i^H \mathbf{x}_i$, where $\mathbf{w}_i$ is the receiver beamforming vector. The signal to noise ratio at the output of the ith beamformer is given by

$$\Gamma_i = \frac{P_i G_{ii} \mathbf{w}_i^H \mathbf{a}_{ii} \mathbf{a}_{ii}^H \mathbf{w}_i}{\sum_{m \neq i} P_m G_{mi} \mathbf{w}_i^H \mathbf{a}_{mi} \mathbf{a}_{mi}^H \mathbf{w}_i + N_i \mathbf{w}_i^H \mathbf{w}_i}. \tag{7}$$

The following algorithm has been proposed in [8], which achieves the jointly optimal power allocations and beamforming weight vectors.

A. Receiver-Only Beamforming

The nth iteration of the algorithm is as follows.

1) $\mathbf{w}_i^{(n+1)}$ is computed at each receiver i such that the sum of the noise and the cochannel interference is minimized under the condition of constant gain for the direction of interest, i.e.,

$$\mathbf{w}_i^{(n+1)} = \arg\min_{\mathbf{w}_i} \left\{ \sum_{m \neq i} P_m^{(n)} G_{mi} g_{mi}(\mathbf{w}_i, \mathbf{a}_{mi}) + N_i \mathbf{w}_i^H \mathbf{w}_i \right\},$$

subject to $\mathbf{w}_i^H \mathbf{a}_{ii} = 1, \quad (i = 1, \ldots, M)$

where $g_{mi}(\mathbf{w}_i, \mathbf{a}_{mi}) = \left\| \mathbf{w}_i^H \mathbf{a}_{mi} \right\|^2$.

2) The updated power vector $\mathbf{P}^{(n+1)}$ is then obtained by

$$P_i^{(n+1)} = \frac{\gamma_0}{G_{ii}} \left\{ \sum_{m \neq i} P_m^{(n)} G_{mi} g_{mi} \left(\mathbf{w}_i^{(n+1)}, \mathbf{a}_{mi} \right) + N_i \left(\mathbf{w}_i^{(n+1)} \right)^H \mathbf{w}_i^{(n+1)} \right\}, \ (i = 1, \ldots, M)$$

i.e., by performing one power control iteration with the receiver weight vector $\mathbf{w}_i^{(n+1)}$.

It has been shown in [10] that the above algorithm converges to the optimal power allocation and beamforming vectors if there exists any.

In the transmit diversity problem, the weight vectors are applied before the transmission. Consider the downlink scenario for this problem. Denote the transmit diversity weight vector for the ith base station by $\tilde{\mathbf{w}}_i$ and the signal power before the beamformer by $\tilde{P}_i$. The received signal at the ith mobile is given by

$$x_i = \sum_b \tilde{\mathbf{w}}_b^H \mathbf{a}_{ib} \sqrt{\tilde{P}_b G_{ib}} \tilde{s}_b + \tilde{n}_i$$

where $\tilde{s}_b$ is the transmitted message signal by the bth base station and $\tilde{n}_i$ is the thermal noise at the ith mobile. It has been shown that the SINR at the ith mobile is given by

$$\Gamma_i = \frac{\tilde{P}_i G_{ii} \tilde{\mathbf{w}}_i^H \mathbf{a}_{ii} \mathbf{a}_{ii}^H \tilde{\mathbf{w}}_i}{\sum_{b \neq i} \tilde{P}_b G_{ib} \tilde{\mathbf{w}}_b^H \mathbf{a}_{ib} \mathbf{a}_{ib}^H \tilde{\mathbf{w}}_b + \tilde{N}_i}. \quad (8)$$

The following algorithm has been proposed in [11], which can achieve an optimal solution for the downlink problem.

B. Transmitter-Only Beamforming

The algorithm steps at the nth iteration are as follows:

1) beamforming

$$\tilde{\mathbf{w}}_i^{(n+1)} = \arg\min_{\tilde{\mathbf{w}}_i} \left\{ \sum_{m \neq i} P_m^{(n)} G_{mi} g_{mi} (\tilde{\mathbf{w}}_i, \mathbf{a}_{mi}) + \tilde{\mathbf{w}}_i^H \tilde{\mathbf{w}}_i \right\}$$

subject to $\tilde{\mathbf{w}}_i^H \mathbf{a}_{ii} = 1, \quad (i = 1, \ldots, M)$;

2) virtual uplink power vector update

$$P_i^{(n+1)} = \frac{\gamma_0}{G_{ii}} \left\{ \sum_{m \neq i} P_m^{(n)} G_{mi} g_{mi} \left(\tilde{\mathbf{w}}_i^{(n+1)}, \mathbf{a}_{mi} \right) + \left(\tilde{\mathbf{w}}_i^{(n+1)} \right)^H \tilde{\mathbf{w}}_i^{(n+1)} \right\}, \quad (i = 1, \ldots, M);$$

3) downlink power update

$$\tilde{P}_i^{(n+1)} = \frac{\gamma_0}{G_{ii}} \left\{ \sum_{b \neq i} \tilde{P}_b^{(n)} G_{ib} g_{ib} \left(\tilde{\mathbf{w}}_b^{(n+1)}, \mathbf{a}_{ib} \right) + \tilde{N}_i \right\}, \quad (i = 1, \ldots, M).$$

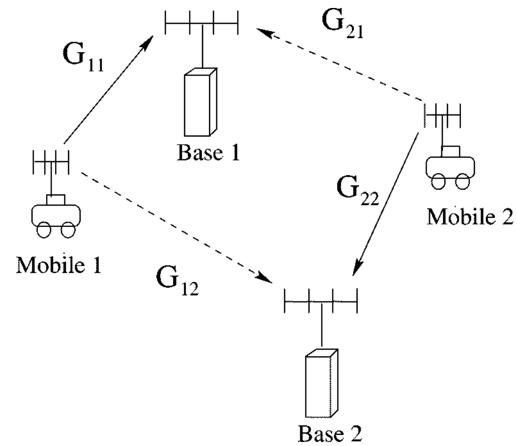

Fig. 1. Two pairs of mobile transmitters and base station receivers with linear adaptive antenna arrays having four elements each.

It has been shown in [11] that the above algorithm converges to a feasible power allocation and beamforming vectors and minimizes the total transmit power in the network.

III. Dual Transmitter Receiver Diversity

Assume that each receiver has a linear adaptive antenna array with K_R elements and each transmitter antenna array has K_T elements. The spacing between the elements is assumed to be half the wavelength.

Fig. 1 depicts two pairs of mobile transmitters and base station receivers with four antenna array elements each.[1] The uplink case will be considered for the clarity of the presentation. Note that the idea and the algorithms are directly applicable to the downlink case, also. In fact, the framework is general enough to cover even the peer-to-peer network, where wireless nodes can communicate with one another directly without having to go through a base station.

Fig. 2 shows the jth transmitter antenna array and the ith receiver antenna array, where the transmitter beamforming vector is denoted by $\tilde{\mathbf{w}}_j$ and the receiver beamforming vector is $\mathbf{w}_i$. The channel response of the jth mobile at the ith base station can be represented as a matrix $\mathbf{A}_{ji}$ of dimension $K_R \times K_T$. The (k, l)th element of channel response matrix $\mathbf{A}_{ji}$ is denoted by $\mathbf{A}_{ji}[k][l]$. Note that we do not assume rank one for the channel response matrix.

The received signal at the ith base station receiver is obtained as a weighted sum of the received signals at each array element

$$x_i = \sum_{k=1}^{K_R} w_i^*[k] r_i[k] \quad (9)$$

where w^* denotes the complex conjugate of w and $r_i[k]$ is the received signal at the kth element of ith receiver antenna array from M transmitters given by

$$r_i[k] = \sum_{j=1}^{M} \sum_{l=1}^{K_T} A_{ji}[k][l] \tilde{w}_j^*[l] \sqrt{P_j G_{ji}} s_j + n_i[k] \quad (10)$$

[1]The figure should be interpreted as a notational reference. The physical locations of the base stations may actually be the same in CDMA systems and multiple mobiles can be assigned to the same base station.

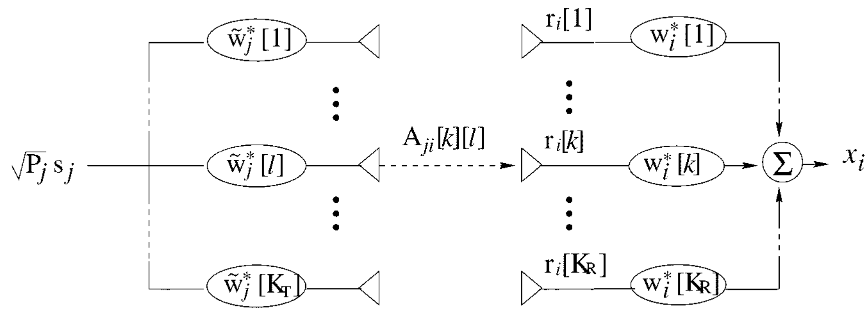

Fig. 2. Antenna arrays of the jth transmitter and the ith receiver and the spatial signature $\mathbf{A}_{ji}$.

where s_j is the message signal transmitted by mobile j and $n_i[k]$ is the thermal noise at the input of the kth array element of receiver i. Inserting (10) into (9) gives

$$\begin{aligned} x_i &= \sum_{k=1}^{K_R} w_i^*[k] \left(\sum_{j=1}^{M} \sum_{l=1}^{K_T} A_{ji}[k][l] \tilde{w}_j^*[l] \sqrt{P_j G_{ji}} s_j + n_i[k] \right) \\ &= \sum_{j=1}^{M} \mathbf{w}_i^H \mathbf{A}_{ji} \tilde{\mathbf{w}}_j^* \sqrt{P_j G_{ji}} s_j + \mathbf{w}_i^H \mathbf{n}_i \end{aligned}$$

where $\mathbf{n}_i$ is the thermal noise vector at the ith receiver. If we assume that the noise and the signals are uncorrelated and zero-mean and that the signals are orthonormal, then the average power of the received signal at receiver i is

$$\begin{aligned} E\left[x_i x_i^H\right] &= \sum_{j=1}^{M} \mathbf{w}_i^H \mathbf{A}_{ji} \tilde{\mathbf{w}}_j^* \left\{ \mathbf{w}_i^H \mathbf{A}_{ji} \tilde{\mathbf{w}}_j^* \right\}^H P_j G_{ji} \\ &\quad + \mathbf{w}_i^H E\left[\mathbf{n}_i \mathbf{n}_i^H\right] \mathbf{w}_i \\ &= \sum_{j=1}^{M} P_j G_{ji} \left\| \mathbf{w}_i^H \mathbf{A}_{ji} \tilde{\mathbf{w}}_j^* \right\|^2 + N_i \mathbf{w}_i^H \mathbf{w}_i \end{aligned}$$

where N_i is the noise power at the input of each array element. Therefore, the SINR at the ith base station receiver is given by

$$\Gamma_i = \frac{P_i G_{ii} \mathbf{w}_i^H \alpha_{ii} \alpha_{ii}^H \mathbf{w}_i}{\sum_{j \neq i}^{M} P_j G_{ji} \mathbf{w}_i^H \alpha_{ji} \alpha_{ji}^H \mathbf{w}_i + N_i \mathbf{w}_i^H \mathbf{w}_i} \tag{11}$$

where α_{ji} is defined as $\alpha_{ji} = \mathbf{A}_{ji} \tilde{\mathbf{w}}_j^*$.

The above SINR expression can also be used for a spread spectrum system if we assume that the spreading sequences of the interfering users appear as mutually uncorrelated noise [10]. The only difference will be the addition of the processing gain term, which can be absorbed into the target SINR.

The following two problems will be considered for the joint power control and beamforming, where three sets of variables—the transmitter powers, transmitter beamforming vectors, and receiver beamforming vectors—are to be found as well.

Problem 1: Maximize the minimum SINR over all receivers, for all combinations of power vector $\mathbf{P}$, receiver beamforming vectors $\mathbf{w}_i$'s, and transmitter beamforming vectors $\tilde{\mathbf{w}}_i$'s.

Problem 2: Minimize the sum of the total transmitter powers $\sum_{i=1}^{M} P_i \tilde{\mathbf{w}}_i^H \tilde{\mathbf{w}}_i$, subject to the SINR constraints $\Gamma_i \geq \gamma_0$, for all i, where γ_0 is an achievable system protection ratio.

If the transmitter weights are fixed, then we have the special case of joint power control and receiver beamforming. If the receiver weights are fixed, then we have the special case of transmitter beamforming and power control. When both transmitter and receiver beamforming can be performed simultaneously, we have the general case that is addressed in this paper.

Both problems can be thought of as multivariable joint optimization problems. There are three sets of variables: the transmitter power vector $\mathbf{P}$, the receiver beamforming vectors $\mathbf{w}_i$'s, and the transmitter beamforming vectors $\tilde{\mathbf{w}}_i$'s. One approach to the optimization is to optimize with respect to one set of variables in turn while having the other two fixed. Note that the actions taken at each step exactly coincide with the ones in the previous works, i.e., the joint receiver beamforming and power control [8], [10] and the joint transmit beamforming and power control [9], [11]. Another possibility is to optimize with respect to two sets of variables in turn while having the remaining set fixed. In the following, we will develop algorithms that solve the two problems with the first method.

The optimal receiver beamforming vector for fixed transmitter powers and fixed transmitter beamforming vectors can be obtained from the MVDR beamformer and is what minimizes the sum of noise and cochannel interference at receiver i, i.e.,

$$\underline{\mathbf{w}}_i = \arg\min_{\mathbf{w}_i} \left(\sum_{j \neq i}^{M} P_j G_{ji} \mathbf{w}_i^H \alpha_{ji} \alpha_{ji}^H \mathbf{w}_i + N_i \mathbf{w}_i^H \mathbf{w}_i \right) \tag{12}$$

subject to the constraint that the gain at the direction of interest is equal to unity, i.e., $\mathbf{w}_i^H \alpha_{ii} = 1$. The solution to this problem is given by [3]

$$\underline{\mathbf{w}}_i = \frac{\Phi_i^{-1} \alpha_{ii}}{\alpha_{ii}^H \Phi_i^{-1} \alpha_{ii}} \tag{13}$$

where Φ_i is the correlation matrix given by [12]

$$\Phi_i = \sum_{j=1}^{M} P_j G_{ji} \alpha_{ji} \alpha_{ji}^H + N_i \mathbf{I}. \tag{14}$$

In order to find the optimal transmitter beamforming vector for fixed receiver weights and transmitter powers, the *virtual downlink* concept [9], [11] is used, where the transmitters and receivers interchange locations. It should be noted that there is no assumption about the reciprocity of the network here. Using the transmit beaforming vectors, we can rewrite (11) as follows:

$$\Gamma_i = \frac{P_i G_{ii} \tilde{\mathbf{w}}_i^H \tilde{\alpha}_{ii} \tilde{\alpha}_{ii}^H \tilde{\mathbf{w}}_i}{\sum_{j\neq i}^{M} P_j G_{ji} \tilde{\mathbf{w}}_j^H \tilde{\alpha}_{ij} \tilde{\alpha}_{ij}^H \tilde{\mathbf{w}}_j + N_i \mathbf{w}_i^H \mathbf{w}_i} \tag{15}$$

where $\tilde{\alpha}_{ij}$ is defined as $\tilde{\alpha}_{ij} = \mathbf{A}_{ji}^T \mathbf{w}_i^*$. From (15), in order to provide the required link quality, the SINR at link i should be at least γ_0, i.e.,

$$P_i G_{ii} \tilde{\mathbf{w}}_i^H \tilde{\alpha}_{ii} \tilde{\alpha}_{ii}^H \tilde{\mathbf{w}}_i \geq \gamma_0 \left(\sum_{j\neq i}^{M} P_j G_{ji} \tilde{\mathbf{w}}_j^H \tilde{\alpha}_{ij} \tilde{\alpha}_{ij}^H \tilde{\mathbf{w}}_j + N_i \mathbf{w}_i^H \mathbf{w}_i \right).$$

Noting that the minimum total power is achieved when the SINR is equal to the target value, this constraint can be written in matrix form as

$$\mathbf{P} = \gamma_0 \mathbf{DFP} + \mathbf{u} \tag{16}$$

where $\mathbf{D}$ is defined as

$$[\mathbf{D}]_{ij} = \begin{cases} \left(G_{ii} \tilde{\mathbf{w}}_i^H \tilde{\alpha}_{ii} \tilde{\alpha}_{ii}^H \tilde{\mathbf{w}}_i \right)^{-1} & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases}$$

and $\mathbf{F}$ is defined as

$$[\mathbf{F}]_{ij} = \begin{cases} G_{ji} \tilde{\mathbf{w}}_j^H \tilde{\alpha}_{ij} \tilde{\alpha}_{ij}^H \tilde{\mathbf{w}}_j & \text{if } i \neq j \\ 0 & \text{if } i = j \end{cases}$$

and $\mathbf{u}$ is

$$[\mathbf{u}]_i = \gamma_0 \frac{N_i \mathbf{w}_i^H \mathbf{w}_i}{G_{ii} \tilde{\mathbf{w}}_i^H \tilde{\alpha}_{ii}^H \tilde{\alpha}_{ii} \tilde{\mathbf{w}}_i}.$$

Let $\tilde{P}_i$ denote the virtual downlink power of base station i. The virtual downlink SINR at mobile i is given by

$$\tilde{\Gamma}_i = \frac{\tilde{P}_i G_{ii} \tilde{\mathbf{w}}_i^H \tilde{\alpha}_{ii} \tilde{\alpha}_{ii}^H \tilde{\mathbf{w}}_i}{\sum_{j\neq i}^{M} \tilde{P}_j G_{ij} \tilde{\mathbf{w}}_i^H \tilde{\alpha}_{ji} \tilde{\alpha}_{ji}^H \tilde{\mathbf{w}}_i + \tilde{\mathbf{w}}_i^H \tilde{\mathbf{w}}_i}. \tag{17}$$

The optimal virtual downlink power vector is obtained when $\tilde{\Gamma}_i = \gamma_0$, which in matrix form is given by

$$\tilde{\mathbf{P}} = \gamma_0 \mathbf{DF}^T \tilde{\mathbf{P}} + \tilde{\mathbf{u}}, \tag{18}$$

where $\tilde{\mathbf{u}}$ is

$$[\tilde{\mathbf{u}}]_i = \gamma_0 \frac{\tilde{\mathbf{w}}_i^H \tilde{\mathbf{w}}_i}{G_{ii} \tilde{\mathbf{w}}_i^H \tilde{\alpha}_{ii}^H \tilde{\alpha}_{ii} \tilde{\mathbf{w}}_i}.$$

The optimal transmitter beamforming vector for fixed virtual downlink powers and fixed receiver beamforming vectors is that which minimizes the sum of virtual noise and interference at mobile i, i.e.,

$$\underline{\tilde{\mathbf{w}}}_i = \arg\min_{\tilde{\mathbf{w}}_i} \left(\sum_{j\neq i}^{M} \tilde{P}_j G_{ij} \tilde{\mathbf{w}}_i^H \tilde{\alpha}_{ji} \tilde{\alpha}_{ji}^H \tilde{\mathbf{w}}_i + \tilde{\mathbf{w}}_i^H \tilde{\mathbf{w}}_i \right) \tag{19}$$

subject to the constraint that the gain at the direction of interest is equal to unity, i.e., $\tilde{\mathbf{w}}_i^H \tilde{\alpha}_{ii} = 1$. The solution to this problem can be obtained using the same method as in the receiver beamforming vector calculation, i.e.,

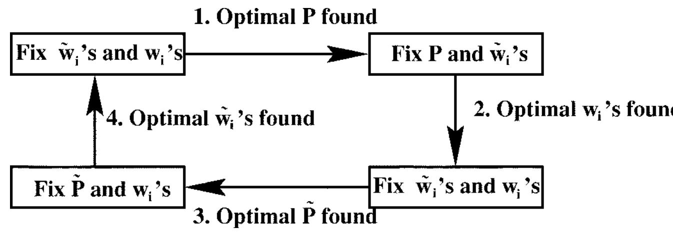

Fig. 3. Block diagram of the maxmin SINR algorithms.

$$\underline{\tilde{\mathbf{w}}}_i = \frac{\tilde{\Phi}_i^{-1} \tilde{\alpha}_{ii}}{\tilde{\alpha}_{ii}^H \tilde{\Phi}_i^{-1} \tilde{\alpha}_{ii}} \tag{20}$$

where $\tilde{\Phi}_i$ is given by

$$\tilde{\Phi}_i = \sum_{j=1}^{M} \tilde{P}_j G_{ij} \tilde{\alpha}_{ji} \tilde{\alpha}_{ji}^H + \mathbf{I}. \tag{21}$$

IV. Proposed Algorithms

In this section, we propose some algorithms along the lines of the optimization principles mentioned earlier. It is assumed that the channel and array responses from all transmitters to all receivers is fully known.

A. Maxmin SINR Algorithm

An algorithm is presented that finds the maximum of the minimum SINR over all receivers. Fig. 3 is a block diagram illustrating the approach that is taken to jointly optimize the three sets of variables by optimizing one set of variables in turn while having the other two fixed.

Algorithm A:

1) Calculate the maximum of the minimum SINR for fixed transmitter and receiver weights and compute $\mathbf{P}$ that maximizes the minimum SINR over all receivers, i.e.,

$$\gamma_{\max} = \frac{1}{\rho(\mathbf{DF})}$$

and the normalized eigenvector $\mathbf{P}$, which satisfies

$$\mathbf{P} = \gamma_{\max} \mathbf{DFP}.$$

2) Calculate receiver weights to maximize SINR for fixed uplink powers and transmitter weights

$$\underline{\mathbf{w}}_i = \arg\min_{\mathbf{w}_i} \left(\sum_{j\neq i}^{M} P_j G_{ji} \mathbf{w}_i^H \alpha_{ji} \alpha_{ji}^H \mathbf{w}_i \right),$$

subject to $\mathbf{w}_i^H \alpha_{ii} = 1, \quad (i = 1, \ldots, M)$.

3) Calculate the maximum of the minimum SINR for fixed transmitter and receiver weights and compute $\tilde{\mathbf{P}}$ that maximizes the minimum SINR over all virtual downlink transmitters, i.e.,

$$\gamma_{\max} = \frac{1}{\rho(\mathbf{DF^T})}$$

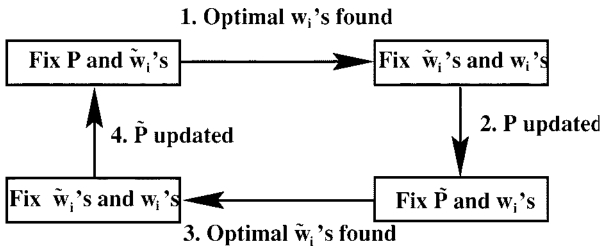

Fig. 4. Block diagram of the minimum transmitter power algorithm.

and the normalized eigenvector $\tilde{\mathbf{P}}$, which satisfies

$$\tilde{\mathbf{P}} = \gamma_{\max}\mathbf{D}\mathbf{F}^T\tilde{\mathbf{P}}.$$

4) Calculate transmitter weights to maximize SINR for fixed virtual downlink powers and receiver weights

$$\underline{\tilde{\mathbf{w}}}_i = \arg\min_{\tilde{\mathbf{w}}_i}\left(\sum_{j\neq i}^{M}\tilde{P}_j G_{ij}\tilde{\mathbf{w}}_i^H\tilde{\alpha}_{ji}\tilde{\alpha}_{ji}^H\tilde{\mathbf{w}}_i\right),$$

subject to $\tilde{\mathbf{w}}_i^H\tilde{\alpha}_{ii} = 1, \quad (i = 1,\ldots,M).$

5) Go to step 1 and repeat the iteration.

Algorithms A produces the maximum of the minimum SINR $\gamma_{\max}$ over all receivers, which can be used directly as a means to compare the performances of the systems having different number of array elements. This value $\gamma_{\max}$ can also be used to compare the capacity of the network; the larger $\gamma_{\max}$ is, the more mobiles can be supported.

B. Minimum Transmitter Power Algorithms

In this section, iterative algorithms for problem 2 are proposed. Note that the following two methods differ only in determining the transmit beamformer weights.

1) Virtual Downlink Method: This method can be viewed as a combination of the algorithms in [10] and [11]. The power update iteration is motivated by the fact that if there exists a feasible power vector for a fixed set of transmitter and receiver weights then the algorithm converges. If there is no feasible power vector for a fixed set of weights, then the algorithm diverges. Fig. 4 is a block diagram illustrating the algorithm steps. One can observe that the steps 1 and 2 are taken with transmitter beamforming vectors $\tilde{\mathbf{w}}_i$'s fixed, which are exactly the same two steps of the joint receiver beamforming and power control algorithm [8], [10]. On the other hand, if we omit step 1, then the remaining three steps are exactly the same as the joint transmit beamforming and power control algorithm [9], [11].

Algorithm B:

1) Calculate receiver weights to maximize SINR for fixed uplink powers and transmitter weights

$$\mathbf{w}_i^{(n+1)} = \arg\min_{\mathbf{w}_i}\left(\sum_{j\neq i}^{M}P_j^{(n)}G_{ji}\mathbf{w}_i^H\alpha_{ji}\alpha_{ji}^H\mathbf{w}_i + N_i\mathbf{w}_i^H\mathbf{w}_i\right)$$

subject to $\mathbf{w}_i^H\alpha_{ii} = 1, \quad (i = 1,\ldots,M).$

2) Update the uplink powers

$$P_i^{(n+1)} = \frac{\gamma_0}{G_{ii}}\left\{\sum_{j\neq i}G_{ji}\left(\mathbf{w}_i^{(n+1)}\right)^H\alpha_{ji}\alpha_{ji}^H\mathbf{w}_i^{(n+1)}P_j^{(n)} + N_i\left(\mathbf{w}_i^{(n+1)}\right)^H\mathbf{w}_i^{(n+1)}\right\},$$

$(i = 1,\ldots,M).$

3) Calculate transmitter weights to maximize SINR for fixed virtual downlink powers and receiver weights

$$\tilde{\mathbf{w}}_i^{(n+1)} = \arg\min_{\tilde{\mathbf{w}}_i}\left(\sum_{j\neq i}^{M}\tilde{P}_j^{(n)}G_{ij}\tilde{\mathbf{w}}_i^H\tilde{\alpha}_{ji}\tilde{\alpha}_{ji}^H\tilde{\mathbf{w}}_i + \tilde{\mathbf{w}}_i^H\tilde{\mathbf{w}}_i\right)$$

subject to $\tilde{\mathbf{w}}_i^H\tilde{\alpha}_{ii} = 1, \quad (i = 1,\ldots,M).$

4) Update the virtual downlink powers

$$\tilde{P}_i^{(n+1)} = \frac{\gamma_0}{G_{ii}}\left\{\sum_{j\neq i}G_{ij}\left(\tilde{\mathbf{w}}_i^{(n+1)}\right)^H\tilde{\alpha}_{ji}\tilde{\alpha}_{ji}^H\tilde{\mathbf{w}}_i^{(n+1)}\tilde{P}_j^{(n)} + \left(\tilde{\mathbf{w}}_i^{(n+1)}\right)^H\tilde{\mathbf{w}}_i^{(n+1)}\right\}, \quad (i = 1,\ldots,M).$$

5) Go to step 1 and repeat the iteration.

As a result of this algorithm, a power vector and a set of receiver weights and transmitter weights are found. The sum of the total transmitted powers

$$\sum_{i=1}^{M}P_i\tilde{\mathbf{w}}_i^H\tilde{\mathbf{w}}_i \tag{22}$$

can be obtained. Note that if γ_0 is not achievable, then Algorithm B diverges.

2) Simple Gain Maximization Method: In this section, we consider another approach to the transmit beamforming.

Algorithm C:

1) Calculate receiver weights to maximize SINR for fixed uplink powers and transmitter weights

$$\mathbf{w}_i^{(n+1)} = \arg\min_{\mathbf{w}_i}\left(\sum_{j\neq i}^{M}P_j^{(n)}G_{ji}\mathbf{w}_i^H\alpha_{ji}\alpha_{ji}^H\mathbf{w}_i + N_i\mathbf{w}_i^H\mathbf{w}_i\right)$$

subject to $\mathbf{w}_i^H\alpha_{ii} = 1, \quad (i = 1,\ldots,M).$

2) Update the uplink powers

$$P_i^{(n+1)} = \frac{\gamma_0}{G_{ii}}\left\{\sum_{j\neq i}G_{ji}\left(\mathbf{w}_i^{(n+1)}\right)^H\alpha_{ji}\alpha_{ji}^H\mathbf{w}_i^{(n+1)}P_j^{(n)} + N_i\left(\mathbf{w}_i^{(n+1)}\right)^H\mathbf{w}_i^{(n+1)}\right\}, \ (i = 1,\ldots,M).$$

3) Beamforming using simple maximization of the antenna gain toward the first element of the receiver antenna array is given by

$$\tilde{\mathbf{w}}_i^{(n+1)} = \arg\max_{\tilde{\mathbf{w}}_i} \left\| \tilde{\mathbf{w}}_i^H \underline{\tilde{\mathbf{a}}}_{ii} \right\|^2$$
$$\text{subject to } \tilde{\mathbf{w}}_i^H \tilde{\mathbf{w}}_i = \frac{1}{K_T}, \quad (i = 1, \ldots, M)$$

where $\underline{\tilde{\mathbf{a}}}_{ii}$ is defined as the first column of $\mathbf{A}_{ii}^T$.

4) Update the virtual downlink powers

$$\tilde{P}_i^{(n+1)} = \frac{\gamma_0}{G_{ii}} \left\{ \sum_{j \neq i} G_{ij} \left(\tilde{\mathbf{w}}_i^{(n+1)} \right)^H \tilde{\alpha}_{ji} \tilde{\alpha}_{ji}^H \tilde{\mathbf{w}}_i^{(n+1)} \tilde{P}_j^{(n)} + \left(\tilde{\mathbf{w}}_i^{(n+1)} \right)^H \tilde{\mathbf{w}}_i^{(n+1)} \right\}, \quad (i = 1, \ldots, M).$$

5) Go to step 1 and repeat the iteration.

Note that this approach differs from Algorithm B in step 3 only and the optimal transmit beamforming vector $\tilde{\mathbf{w}}_i$ is given by

$$\underline{\tilde{\mathbf{w}}}_i = \frac{1}{K_T} \underline{\tilde{\mathbf{a}}}_{ii}. \tag{23}$$

The motivation for this approach is explained in the following. In step 3 of Algorithm B, we minimize the sum of interference and the thermal noise while having the received signal fixed. The sum of interference term consists of the interference from the same cell base station talking to the other mobiles in the cell and the other cell base stations talking to the mobiles in their cells. Of the two interferences the former is more significant because of the shorter distance, yet it is uncontrollable by transmit beamforming at the mobile since the direction of the interference is exactly the same as the desired signal direction. Therefore, in Algorithm B, we actually minimize only the latter interference and the thermal noise. Now, the thermal noise term is more significant than the interference from the other cell base stations. Therefore, we can simply minimize the thermal noise term only while having a little performance degradation. Interesting fact is that the simple gain maximization is similar to the minimization of the thermal noise term only. Note, however, that the constraints are different; while the constraint for the simple maximization of the signal is the constant magnitude of the weight vector, the constraint for the minimization of the thermal noise term only is the constant antenna gain toward the signal direction. The minimization of the thermal noise term only is given by

$$\tilde{\mathbf{w}}_i = \arg\min_{\tilde{\mathbf{w}}_i} \tilde{\mathbf{w}}_i^H \tilde{\mathbf{w}}_i \text{ subject to } \tilde{\mathbf{w}}_i^H \underline{\tilde{\mathbf{a}}}_{ii} = 1 \tag{24}$$

which has the same optimal solution as (23).

The performance of this simple gain maximization is a little worse than that of Algorithm B, but the convergence to a unique suboptimal point can be shown. Another advantage of the simple gain maximization is that it is simpler to implement than Algorithm B.

V. Simulation Studies

A. Performance Comparison

In this section, using the algorithms proposed, the maximum of the minimum SINR over all receivers and the sum of the total transmitted powers will be presented for systems with different number of antenna array elements for the uplink scenario. Let us refer to the system having K_T transmitter antenna array elements and K_R receiver array elements as *Beamforming* (K_T, K_R). Note that if the number of array elements is one, then the antenna is omnidirectional. The directions of antenna arrays are randomly assigned.

A CDMA network covering the area of $[0.5, 3.5] \times [0.5, 3.5]$ is considered, where nine base stations with K_R element receiver antenna arrays are located on the integer grids and M mobiles with K_T element transmitter antenna arrays are uniformly distributed. We assume that a mobile is assigned to its nearest base station. The link gain is modeled as $G_{ij} = d_{ij}^{-4}$, where d_{ij} is the distance between mobile i and base station j, which ignores the shadow fading. Note that the algorithms would not be changed at all even if we take the effect of fading into account. If there is only one line-of-sight path between transmitter j and receiver i and the distance between them is large enough compared with the antenna separation, then the rank of the matrix $\mathbf{A}_{ji}$ is one and can be given by

$$\mathbf{A}_{ji} = \mathbf{a}_{ji} \tilde{\mathbf{a}}_{ij}^T \tag{25}$$

where $\mathbf{a}_{ji}$ is the spatial signature of mobile j at base i and $\tilde{\mathbf{a}}_{ij}$ is the spatial signature of base i at mobile j. Note that this assumption is only used for the simulation and is not necessary for our formulation and proposed algorithms.

An observation from the simulations is that all the algorithms always converged to a unique solution as well as the corresponding three sets of variables regardless of the initial conditions. This implies that the algorithms are very likely to find the optimal solutions.

Fig. 5 shows the maximum of the minimum SINR over all receivers versus the number of mobiles in the network. For a given SINR threshold, *Beamforming* (4,4) can support more mobiles than any other system considered. For example, when $\gamma_0 = 0.0304$, *Beamforming* (1,4) can support up to 800 mobiles, while *Beamforming* (4,4) can support more than 1000 mobiles. Now, if we compare the cases with comparable amount of hardware, *Beamforming* (1,4) showed better performance than *Beamforming* (2,2) and *Beamforming* (4,1). This is so because in the uplink of CDMA systems the significant portion of the cochannel interference comes from the same cell users, which can only be combatted by the receiver beamforming at the base stations and not by transmit beamforming at the mobiles since the transmitter antenna gains of the in-cell interferers are locked at unity by the transmit beamforming.

Fig. 6 shows the average transmitted power per mobile $(1/M) \sum_{i=1}^{M} P_i \tilde{\mathbf{w}}_i^H \tilde{\mathbf{w}}_i$ versus the number of mobiles in the system when $\gamma_0 = 0.0304$ used in [2]. This SINR threshold results in acceptable bit error rate only in CDMA systems where there is a processing gain of the order of 128 or more. The transmitted powers can be reduced by a factor equal to the

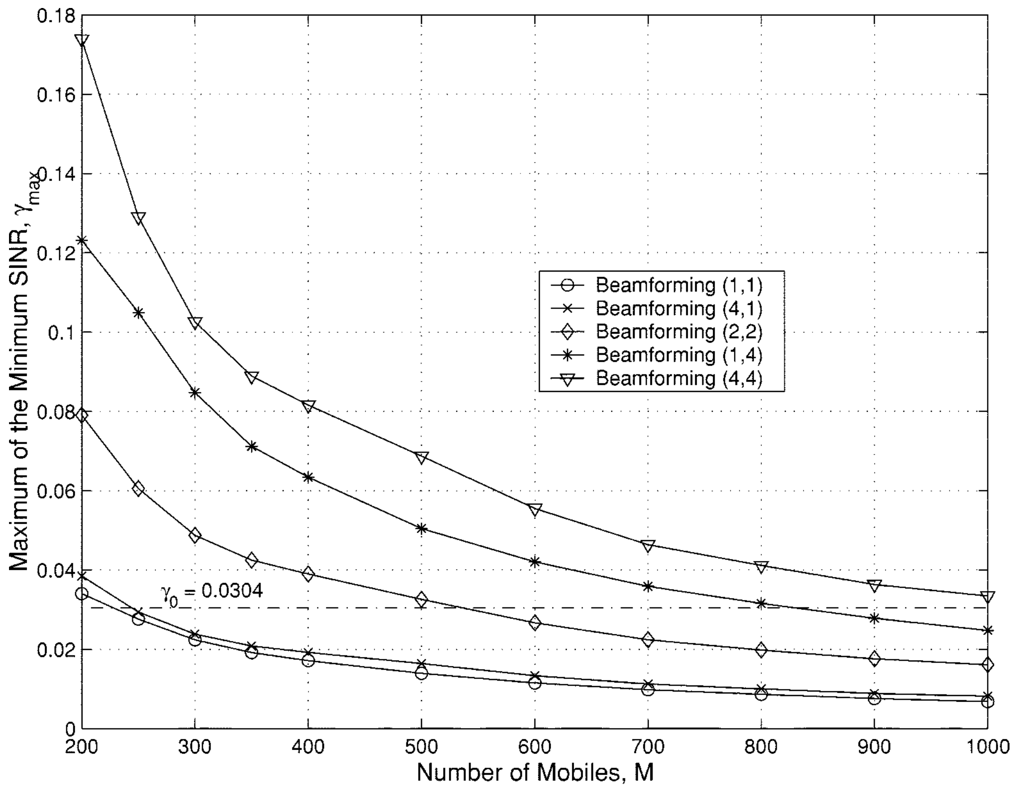

Fig. 5. Maximum of the minimum SINR versus number of mobiles.

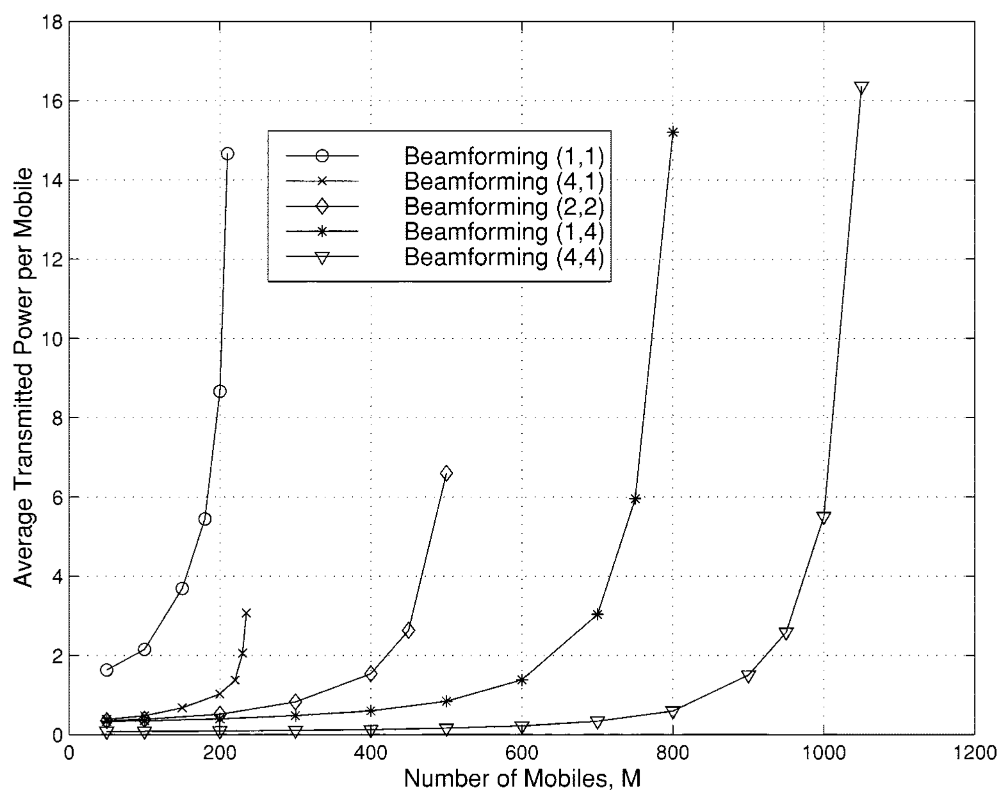

Fig. 6. Average transmitted power per mobile versus number of mobiles when $\gamma_0 = 0.0304$.

number of array elements or more as the number of mobiles increases. Note that these results are consistent with the previous results from Fig. 5, i.e., as the network capacity is approached the transmitted power increases abruptly. For the same reason given in the previous paragraph, *Beamforming* (1,4) performed better than *Beamforming* (2,2) and *Beamforming* (4,1), which

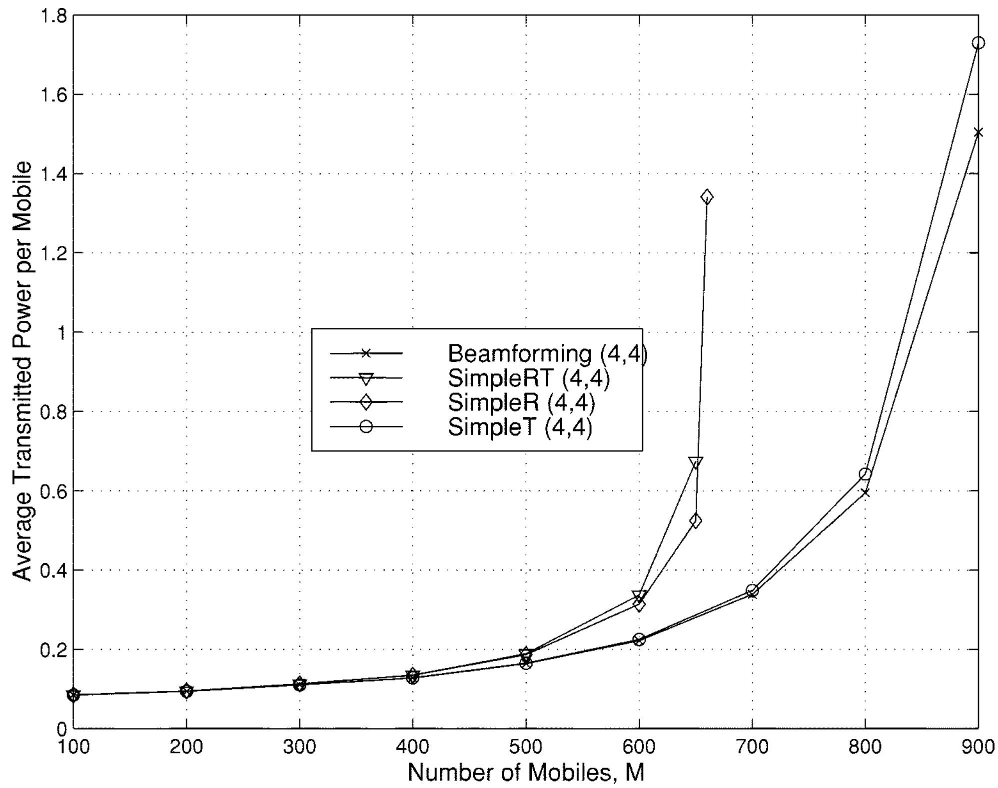

Fig. 7. Average mobile transmitted power versus number of users for different methods of beamforming.

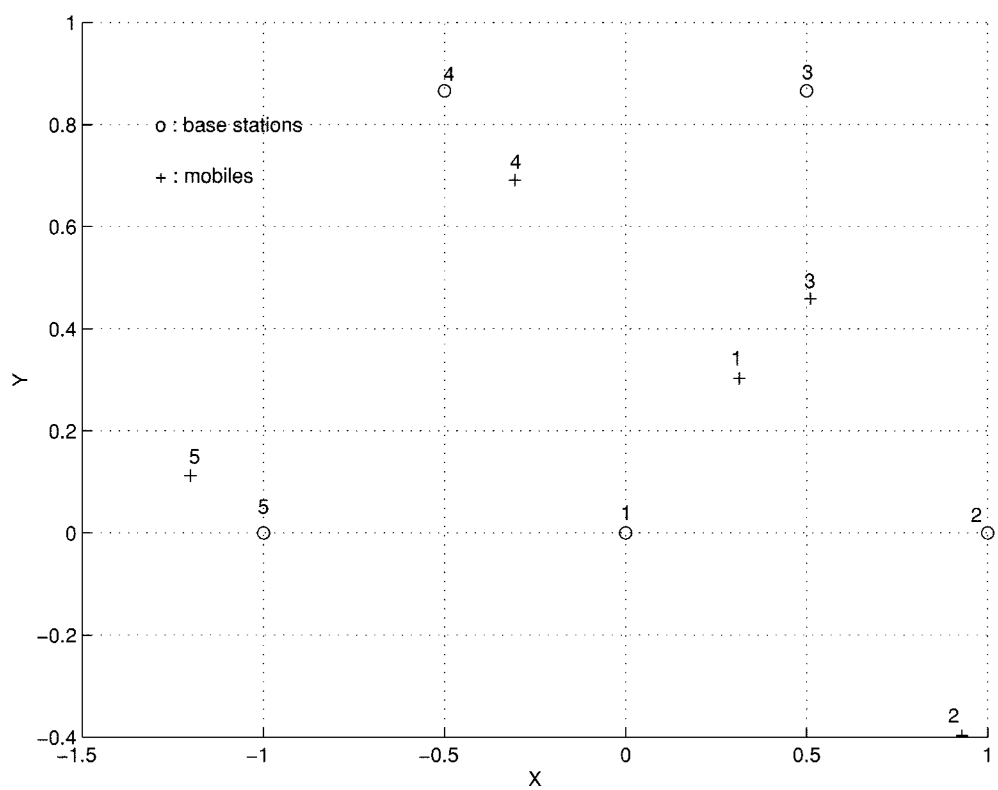

Fig. 8. Locations of the mobiles and the base stations.

suggests that increasing the number of elements at the base stations increases the uplink capacity more than increasing the number of elements at the mobiles.

The simple gain maximization method (Algorithm C) is compared with the virtual downlink method (Algorithm B) in Fig. 7. Beamforming (4,4) is the virtual downlink method. SimpleRT

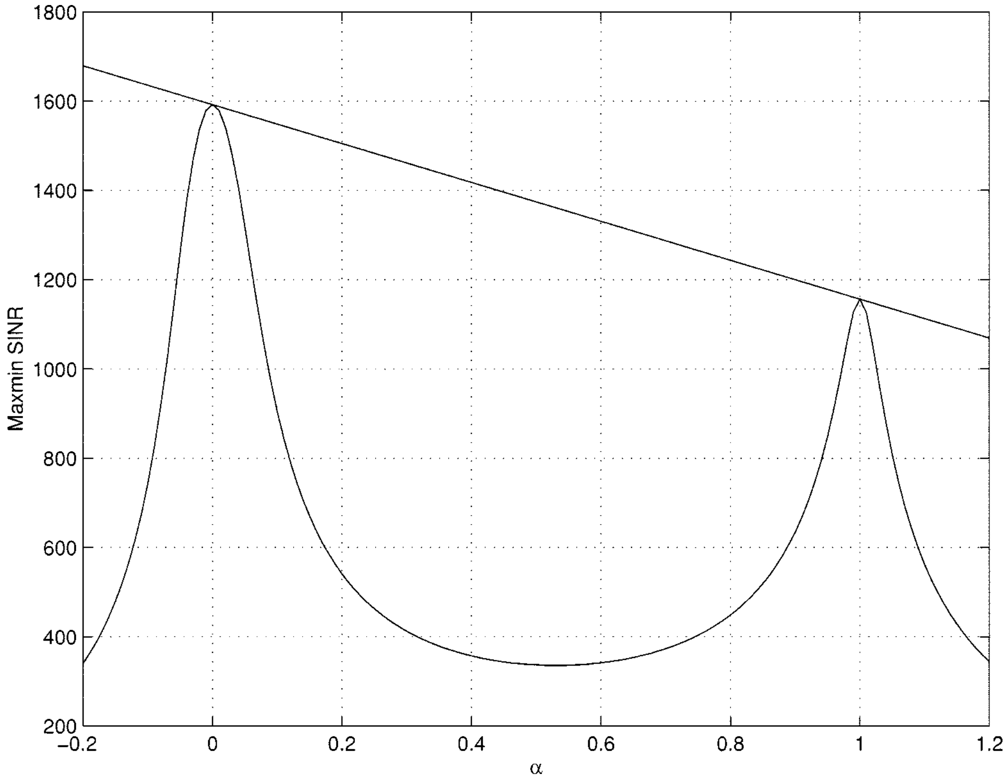

Fig. 9. Local concavity of the maxmin SINR.

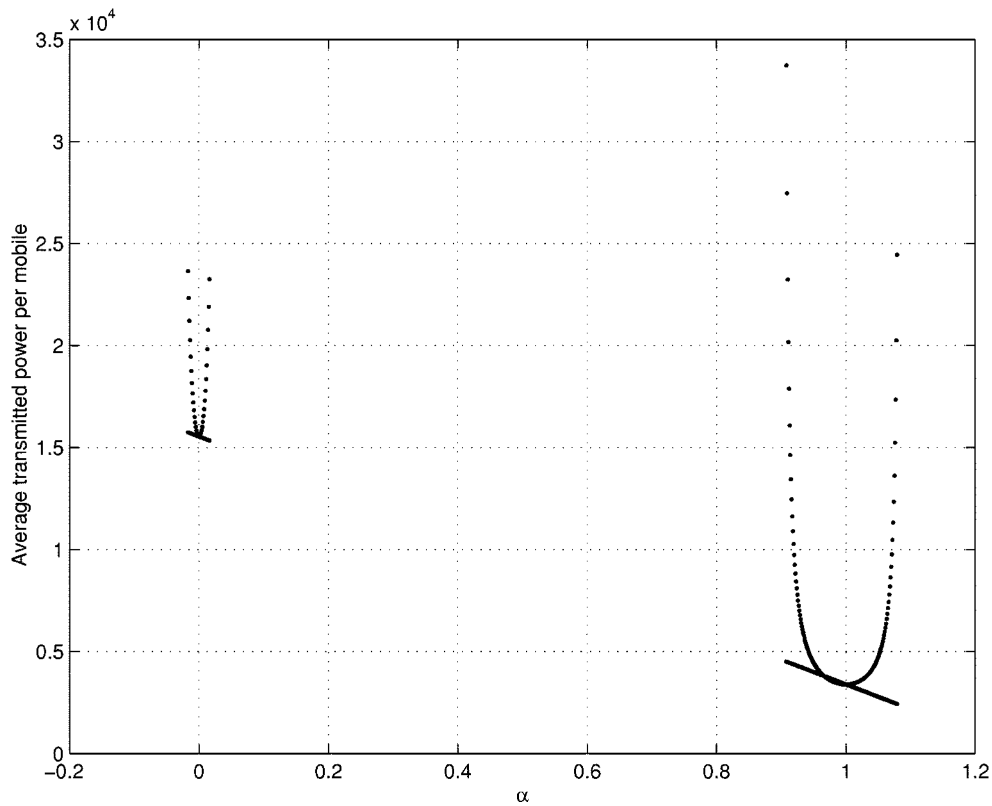

Fig. 10. Local convexity of the average transmitted power.

(4,4) is using simple gain maximization at both transmitters and receivers, while SimpleR (SimpleT) is using simple gain maximization of the signal at the receivers (transmitters) only. One can observe that SimpleT (4,4) performs almost as well as Beamforming (4,4), which supports the motivation for Algorithm C for the uplink of a CDMA system.

B. Multiple Local Optimum Solutions

In this section, an instance where multiple local optimum solutions of the virtual downlink method (Algorithms A and B) were observed is introduced. Note that this phenomenon has only been observed in systems where the number of interferers is relatively small compared with the number of array elements.

The system under consideration consists of five pairs of mobiles and base stations having two array elements each. The locations of the mobiles and the base stations are depicted in Fig. 8.

Without beamforming, the maxmin SINR was 4.6003. However, with joint transmitter and receiver beamforming, the convergent point of Algorithm A was not unique. They were 163.1, 527.5, 816.4, 1156.6, and 1592.2, etc.

The local concavity of the maxmin SINR can be seen by computing the maxmin SINR of the system with linear combination of any two different convergent beamforming vectors. If we refer to one set of convergent beamforming vectors by $\mathbf{w}_i^1$ and $\tilde{\mathbf{w}}_i^1$ and the other set by $\mathbf{w}_i^2$ and $\tilde{\mathbf{w}}_i^2$, the midpoints can be obtained from

$$\begin{cases} \mathbf{w}_i^m &= \alpha \mathbf{w}_i^1 + (1-\alpha)\mathbf{w}_i^2 \\ \tilde{\mathbf{w}}_i^m &= \alpha \tilde{\mathbf{w}}_i^1 + (1-\alpha)\tilde{\mathbf{w}}_i^2. \end{cases} \tag{26}$$

Fig. 9 shows the curve showing the local concavity as α varies.

With the target SINR 1000.0, Algorithm B converged to more than one point. The resulting average transmitted power were 3387.4 and 15 535.7. From (26), a curve that shows the local convexity is drawn in Fig. 10.

The multiple local optima phenomenon occurred only when the number of interferers was small enough so that the interference term could be made zero by beamforming, which could not be observed in our simulation results.

VI. Conclusion

The joint beamforming and power control problem was studied in a cellular radio system where both transmitters and receivers have antenna arrays. The problems of interest were: 1) to find the maximum of the minimum SINR over all receivers and 2) to find the transmitter and receiver array weight vectors and transmitter powers that minimize the total transmitted power while satisfying the SINR requirements. Algorithms that solve the two problems were proposed and the network capacity and the average transmitted power per mobile were compared through simulations among systems with several different combinations of the number of array elements. The joint transmitter and receiver beamforming further increases the network capacity and requires less transmitter powers compared with the systems with only transmit beamforming or systems with only receiver beamforming. We could observe that the beamforming at the mobiles is not as much effective as the beamforming at the base stations as far as the uplink of CDMA system is concerned in which case a simple gain maximization method is not a bad alternative.

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