TRANSMIT AND RECEIVE DIVERSITY AND EQUALIZATION IN WIRELESS NETWORKS WITH FADING CHANNELS

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I. ABSTRACT

A joint power control and space-time diversity scheme is proposed for uplink and downlink. In the uplink, mobile powers and equalization/diversity combining vectors at base stations are calculated jointly. The mobile transmitted power is minimized while the Signal to Noise Ratio (SNR) at each link is maintained above a threshold. A multitap transmit diversity scheme for the downlink is also proposed where the transmit weight vectors are adjusted such that the SNR at each mobile is greater than a threshold. The proposed transmit and receive diversity combining schemes can be applied to networks with fading channels and in cases where the number of cochannels and multipaths are larger than the number of antenna elements. The proposed algorithm achieves the optimal solution for the uplink that minimizes the mobile power, and achieves a feasible solution for the downlink if there exists any.

II. INTRODUCTION

The capacity of a cellular system is limited by the cochannel interference (CCI) and Inter-Symbol Interference (ISI). CCI is due to the interference caused by users sharing the same channel. If the delay spread in a multipath channel is larger than a fraction of a symbol, the delayed components cause ISI. In the uplink, adaptive receiver beamforming schemes have been widely used to reduce the interference at the base station. In order to optimally reduce CCI and ISI, the space-time diversity combining has to be implemented jointly. Because of the large delay spread in the wireless channels, the joint space-time processing will improve the performance by reducing the CCI and ISI and increasing the SNR significantly [2]-[4].

Most often, deploying antenna arrays at the mobile is impractical. However, transmit diversity can be deployed at the base station to improve the downlink capacity. In scenarios where antenna arrays are used at transmitters, the beampattern of each antenna array can be adjusted to minimize the induced interference to undesired receivers. The transmit diversity and receiver beamforming are substantially different in nature. Receiver beamforming can be implemented independently at each receiver, without affecting the performance of other links, while transmit beamforming at the transmitter will change the interference to all other receivers. As a result transmit beamforming has to be done jointly in the entire network. Moreover, in receiver beamforming a local feedback from the receiver output is used to adjust the combining vector. In transmit beamforming, the probing has to be done at the mobile, while the beampatterns are adjusted at the base stations [5]. In Time Division Duplex (TDD) systems where the uplink and downlink channels are reciprocal, the uplink channel information can be used for downlink [3], [6].

Transmit beamforming has been of great interest recently [3]-[7]. However, the link quality is not guaranteed in any of the previous works. Also, by looking at adaptive beamforming between a transmitter and only its receiver, they ignored the possible effects that a change of beampattern in a transmitter could have on all receivers in the entire network. The above algorithms are not guaranteed to find a feasible solution for all cochannel links such that the SNR is satisfied at each link.

In [8] we proposed a distributed algorithm that jointly optimizes the mobile transmitted power and the uplink beamforming vector at a base station. In this work we generalize the proposed method in [8] to the joint space-time diversity and power control. In networks with multipath channels, the new algorithm enhances the uplink capacity over the method in [8] significantly. In the proposed algorithm, we calculate the mobile power allocation and multitap receive diversity combining weight vectors such that the mobile transmitted power is minimized, and the SNR at each link is maintained above a threshold.

Regarding the transmit diversity problem, we introduce the notion of maximum achievable capacity in the downlink. Then, we propose an algorithm that jointly finds a set of feasible space-time diversity weight vectors and power allocations to achieve the required SNR at each link. In a TDD system, where the transmit and receive channels are reciprocal, our algorithm uses the uplink weight vectors for the downlink, and calculates the downlink power allocations such that the link quality is satisfied at each mobile. In a Frequency Division Duplex (FDD) system or a TDD system with fading, where the uplink and downlink channels are different, in order to calculate the downlink diversity vectors

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and power allocations, our algorithm requires the downlink channel gains. The downlink channel characteristics need to be measured at the mobile and transmitted to the base station through a feedback channel. In this case, our proposed scheme calculates feasible combining weight vectors using the global channel measurements. We will show that this algorithm will achieve a feasible solution if there exist any.

III. SYSTEM MODEL AND RECEIVE DIVERSITY COMBINING

Consider a set of M cochannel links which may share base stations as in CDMA systems, or may use distinct base stations as in TDMA systems. Each link consists of a mobile and its assigned base station. Assume that at each link there are maximum L paths, and antenna arrays with P elements are used only at base stations. With that as given and the slow fading assumption, the received signal at the ith base station, denoted by $\mathbf{x}_i(k)$, is given by

$$\mathbf{x}_i(k) = \sum_{m=1}^{M} \sum_{n=0}^{N-1} \mathbf{h}_{mi}(n)\sqrt{P_m} s_m(k-n) + \mathbf{n}_i(k), \qquad (1)$$

where P_m is the mth mobile transmitted power, $\mathbf{n}_i(k)$ is the array noise vector at the ith base station, $s_m(k)$ is the mth mobile message signal, and N is the maximum length of channel response. The channel model, including the transmitter and receiver filters and the array response, is considered in a vector channel model $\mathbf{h}_{mi}(n)$ defined as

$$\mathbf{h}_{mi}(n) = [h_{mi}^1(n), \ldots, h_{mi}^P(n)]^T, \qquad (2)$$

where $h_{mi}^p(n)$ is the channel response from the mth mobile to the pth element of the array at the ith base station, sampled at the symbol intervals. However, we are more interested in the matrix presentation of the channel, and multiplication instead of convolution. Therefore we define the channel response matrix $\mathbf{H}_{mi}$ as

$$\mathbf{H}_{mi} = [\mathbf{h}_{mi}(0) \;\; \mathbf{h}_{mi}(1) \;\; \ldots \;\; \mathbf{h}_{mi}(N-1)],$$

and modify (1) as

$$\mathbf{x}_i(k) = \sum_{m=1}^{M} \mathbf{H}_{mi}\sqrt{P_m}\mathbf{s}_m(k) + \mathbf{n}_i(k), \qquad (3)$$

where

$$\mathbf{s}_i(k) = \begin{bmatrix} s_i(k) \\ \vdots \\ s_i(k-N+1) \end{bmatrix}, \quad \text{and} \quad \mathbf{x}_i(k) = \begin{bmatrix} x_{i1}(k) \\ \vdots \\ x_{iP}(k) \end{bmatrix}.$$

In a multitap diversity combiner, shown in Fig. 1, also known as broadband combiner, the received signal and its delayed versions are weighted and combined together. The T blocks in Fig. 1 produce one symbol interval delay, and the combiner simply calculates the weighted sum of its input signals. The output of the diversity combiner can be expressed as

$$y_i(k) = \sum_{q=0}^{Q-1} \mathbf{w}_i^H(q)\mathbf{x}_i(k+q).$$

Define:

$$\mathbf{W}_i = \begin{bmatrix} \mathbf{w}_i(0) \\ \vdots \\ \mathbf{w}_i(Q-1) \end{bmatrix}, \quad \text{and} \quad \mathbf{X}_i(k) = \begin{bmatrix} \mathbf{x}_i(k) \\ \vdots \\ \mathbf{x}_i(k+Q-1) \end{bmatrix}.$$

The diversity combiner output is then given by

$$y_i(k) = \mathbf{W}_i^H\mathbf{X}_i(k).$$

The aim of receiver beamforming is to adjust the weight vectors to achieve maximum signal to interference ratio at the output of combiner. For this purpose we use a training sequence which is correlated with the desired signal, $s_i(n)$. The weight vectors are adjusted during the transmission of the training sequence and are kept constant in between training phases. In the combining process we try to minimize the difference of the output of combiner $\{y_i(k)\}$ and the training sequence $\{d_i(k)\}$:

$$E_{i,min} = \min_{\mathbf{W}_i} E\{|d_i(k) - \mathbf{W}_i^H\mathbf{X}_i(k)|^2\}. \qquad (4)$$

The combining vector $\mathbf{W}_i$ is given by

$$\mathbf{W}_{i,min} = \arg\min_{\mathbf{W}_i} E\{|d_i(k) - \mathbf{W}_i^H\mathbf{X}_i(k)|^2\}. \qquad (5)$$

It can be shown that the optimum combiner coefficients are given by a Weiner solution [1]

$$\mathbf{W}_{i,min} = \Phi_i^{-1}\mathbf{p}_i,$$

where

$$\Phi_i = E\Big(\mathbf{X}_i(k)\mathbf{X}_i^H(k)\Big), \quad \text{and} \quad \mathbf{p}_i = E\Big(d_i^*(k)\mathbf{X}_i(k)\Big). \qquad (6)$$

There are computationally efficient and recursive techniques to solve (5) such as Least Mean Square (LMS) or Recursive Least Square (RLS) [1].

IV. JOINT POWER CONTROL AND RECEIVE DIVERSITY COMBINING

In a network with power control capability, a transmitter power is updated based on the SNR at its receiver. The SNR is a function of receive diversity combining vectors at each receiver. On the other hand, the diversity combining weight vectors are also dependent on the transmitted powers. In the following we consider the joint calculation of combining vectors and allocated powers in a network.

We evaluate the SNR at each combiner as a function of the gain matrix $\mathbf{H}_{mi}$, weight vector $\mathbf{W}_i$, and transmitted powers. For simplicity, the training sequence is considered as a delayed version of the desired signal. That is, $d_i = s_i(k+$

D), where D is chosen to center the space time combiner, i.e., $D = Q/2$ and $Q > N$. The received vector $\mathbf{X}_i(k)$ is given by

$$\mathbf{X}_i(k) = \begin{bmatrix} \sum_{m=1}^{M} \mathbf{H}_{mi}\sqrt{P_m}\mathbf{s}_m(k) + \mathbf{n}_i(k) \\ \vdots \\ \sum_{m=1}^{M} \mathbf{H}_{mi}\sqrt{P_m}\mathbf{s}_m(k+Q-1) + \mathbf{n}_i(k) \end{bmatrix},$$

and the cross correlation vector $\mathbf{p}_i$ can be written as

$$\mathbf{p}_i = E\{s_i(k+Q/2)\mathbf{X}_i(k)\} = \sqrt{P_i}\begin{bmatrix} \mathbf{0} \\ \mathbf{h}_{ii}(0) \\ \vdots \\ \mathbf{h}_{ii}(N-1) \\ \mathbf{0} \end{bmatrix} = \sqrt{P_i}\mathbf{g}_{ii}.$$

The noise vector $\mathbf{n}_i$ consists of spatially and temporally white noise components which are independent of the received signal. That is the correlation matrix, given by (6), can be simplified as

$$\Phi_i = E\{\mathbf{X}_i^H(k)\mathbf{X}_i(k)\} = \sum_{m=1}^{M} P_m E\{\begin{bmatrix} \mathbf{H}_{mi}\mathbf{s}_m(k) \\ \vdots \\ \mathbf{H}_{mi}\mathbf{s}_m(k+Q-1) \end{bmatrix}$$

$$\times\ [\mathbf{s}_m^H(k)\mathbf{H}_{mi}^H \dots \mathbf{s}_m^H(k+Q-1)\mathbf{H}_{mi}^H]\} + N_i\mathbf{I}, \qquad (7)$$

where N_i is the noise power at the input of each array element. We assume the signals transmitted from different sources are uncorrelated, and the signal transmitted from a source is an uncorrelated zero mean sequence of symbols. Then (7) can be simplified as

$$\Phi_i = \sum_{m=1}^{M} P_m \mathbf{G}_{mi} + N_i\mathbf{I}, \qquad (8)$$

$\mathbf{G}_{mi}$ is a block matrix whose pqth block defined by

$$[\mathbf{G}_{mi}]_{pq} = \mathbf{H}_{mi}\mathbf{J}_{p-q}\mathbf{H}_{mi}^H, \qquad (9)$$

where $\mathbf{J}_{p-q}$ is a matrix which only has ones on $(p-q)$th diagonal in parallel with main diagonal elements. The correlation matrix $\mathbf{G}_{mi}$ can be separated into signal and interference matrices:

$$\mathbf{G}_{ii} = \mathbf{G}_{ii}^s + \mathbf{G}_{ii}^I,$$

where $\mathbf{G}_{ii}^s = \mathbf{g}_{ii}\mathbf{g}_{ii}^H$. The power of the desired signal at the output of beamformer is given by $\mathbf{W}_i{}^H\mathbf{G}_{ii}^s\mathbf{W}_i$, and the interference power is $\mathbf{W}_i{}^H\mathbf{G}_{mi}^I\mathbf{W}_i$, where

$$\mathbf{G}_{mi}^I = \begin{cases} \mathbf{G}_{mi} & m \neq i \\ \mathbf{G}_{ii} - \mathbf{G}_{ii}^s & \text{otherwise} \end{cases}. \qquad (10)$$

As a result, the SNR at the beamformer output at the ith link can be written as

$$\Gamma_i = \frac{P_i\mathbf{W}_i^H\mathbf{G}_{ii}^s\mathbf{W}_i}{\sum_m P_m\mathbf{W}_i^H\mathbf{G}_{mi}^I\mathbf{W}_i + N_i\mathbf{W}_i^H\mathbf{W}_i}. \qquad (11)$$

Consider a set of beamforming vectors $\mathbf{A} = \{\mathbf{W}_1, \dots, \mathbf{W}_M\}$. A set of cochannel links is feasible if there exists a power vector $\mathbf{P}$, and a set $\mathbf{A}$ such that the link quality is satisfied for each link. That is,

$$\Gamma_i \geq \gamma_i.$$

For a fixed diversity combiner, the minimal transmitted power is achieved when

$$\gamma_i = \frac{P_i\mathbf{W}_i^H\mathbf{G}_{ii}^s\mathbf{W}_i}{\sum_m P_m\mathbf{W}_i^H\mathbf{G}_{mi}^I\mathbf{W}_i + N_i\mathbf{W}_i^H\mathbf{W}_i}, \quad (i = 1, \dots, M),$$

and transmitted powers can be updated based on a distributed power control ([8]) scheme given by

$$P_i^{n+1} = \frac{\sum_m P_m^n\mathbf{W}_i^H\mathbf{G}_{mi}^I\mathbf{W}_i + N_i\mathbf{W}_i^H\mathbf{W}_i}{\mathbf{W}_i^H\mathbf{G}_{ii}^s\mathbf{W}_i}, \quad (i = 1, \dots, M).$$

Now the problem is defined as to minimize the transmitted power while the link quality is maintained at each link:

$$\min_{\mathbf{A}, P_i} \sum_i P_i,$$

$$\text{such that} \quad \Gamma_i \geq \gamma_i.$$

We can show that if the set of cochannel links is feasible, there exists a set of optimal weight vectors and power allocations, such that the transmitted powers are minimal among all feasible solutions [8]. In order to find the joint power control and combining vector, we use an algorithm similar to [8]. The algorithm steps at the nth iteration are given as follows:

Algorithm A:

- The combiner vector is obtained by

$$\hat{\mathbf{W}}_i^n = \arg\min_{\mathbf{W}_i} E\{|d_i - \mathbf{W}_i{}^H\mathbf{X}_i|^2\}.$$

  which is equivalent to maximizing the SNR [1], i.e.,

$$\hat{\mathbf{W}}_i^n = \arg\max_{\mathbf{W}_i} \frac{\sum_m P_m^n(\hat{\mathbf{W}}_i)^H\mathbf{G}_{mi}^I\hat{\mathbf{W}}_i + N_i(\hat{\mathbf{W}}_i)^H\hat{\mathbf{W}}_i}{(\hat{\mathbf{W}}_i)^H\mathbf{G}_{ii}^s\hat{\mathbf{W}}_i}.$$

- The transmitted power is updated by

$$P_i^{n+1} = \frac{\sum_m P_m^n(\hat{\mathbf{W}}_i^n)^H\mathbf{G}_{mi}^I\hat{\mathbf{W}}_i^n + N_i(\hat{\mathbf{W}}_i^n)^H\hat{\mathbf{W}}_i^n}{(\hat{\mathbf{W}}_i^n)^H\mathbf{G}_{ii}^s\hat{\mathbf{W}}_i^n}.$$

Using the same approach as in [8], we can show that the above algorithm converges to the optimal power allocations and combining vectors such that the transmitted power for each mobile is minimized among all feasible power allocations and combining vectors.

It can be shown that ([9]) the SNR at the output of beamformer can be written as

$$\Gamma_i = \frac{1 - E_{i,min}}{E_{i,min}},$$

where $E_{i,min}$ is given by (4). The power control iteration in the above algorithm is then modified as

$$P_i^{n+1} = P_i^n \frac{\gamma_i}{\Gamma_i} = \gamma_i P_i^n \frac{E_{i,min}}{1 - E_{i,min}}.$$

Therefore, in order to update the transmitted power, $E_{i,min}$ is evaluated at each base station (measured locally) and sent to the assigned mobile. Knowing its previous transmitted power and the target SNR, the mobile will update its power.

V. TRANSMIT SPACE-TIME DIVERSITY

In the following, we assume that only base stations are using antenna arrays, and we will present an algorithm that finds a set of multitap diversity weight vectors for transmitters such that the desired SNR at each mobile is guaranteed. As we will see later, the transmitted power is also controlled by the transmit diversity weight vectors. The block diagram of a multitap transmit diversity system is shown in Fig. 2. For each mobile there is an independent multitap diversity system at the base station.

The received signal at the ith mobile is a superposition of the transmitted signal and its delayed versions through the multipath channel. The transmitted vector by itself is a weighted combination of the desired signal and its delayed versions. Assume that in the steady state, the weight vectors are time independent, and denote the diversity vector at the qth tap of the bth base station by $\tilde{\mathbf{w}}_b(q)$. The received signal is then given by

$$\tilde{y}_i(k) = \sum_{b=1}^{B} \sum_{q=0}^{Q-1} \sum_{n=0}^{N-1} \tilde{\mathbf{w}}_b^H(q)\mathbf{h}_{ib}(n)\sqrt{\tilde{P}_b}\tilde{s}_b(k-n+q) + \tilde{n}_i(k),$$

where $\tilde{s}_b$ is the message signal transmitted from the bth base station to its associated mobile, and $\tilde{P}_b$ is its assigned power. $\tilde{n}_i(k)$ is the thermal noise at the ith mobile, and $\mathbf{h}_{ib}$ is defined as in (2) while the channel response is now associated with downlink. It follows that

$$\tilde{y}_i(k) = \sum_{b=1}^{B} \sum_{q=0}^{Q-1} \tilde{\mathbf{w}}_b^H(q)\mathbf{H}_{ib}\sqrt{P_b}\tilde{\mathbf{s}}_b(k+q) + \tilde{n}_i(k), \qquad (12)$$

where

$$\tilde{\mathbf{s}}_b(k) = \begin{bmatrix} \tilde{s}_b(k) \\ \vdots \\ \tilde{s}_b(k-N+1) \end{bmatrix}.$$

Define:

$$\tilde{\mathbf{W}}_b = \begin{bmatrix} \tilde{\mathbf{w}}_b(0) \\ \vdots \\ \tilde{\mathbf{w}}_b(Q-1) \end{bmatrix}, \text{ and } \tilde{\mathbf{X}}_{ib}(k) = \begin{bmatrix} \tilde{\mathbf{x}}_{ib}(k) \\ \vdots \\ \tilde{\mathbf{x}}_{ib}(k+Q-1) \end{bmatrix},$$

where $\tilde{\mathbf{x}}_{ib}(k) = \mathbf{H}_{ib}\sqrt{P_b}\tilde{\mathbf{s}}(k)$. Then the received signal at the ith receiver is expressed as

$$\tilde{y}_i(k) = \sum_b \tilde{\mathbf{W}}_b^H \tilde{\mathbf{X}}_{ib}(k) + \tilde{n}_i(k). \qquad (13)$$

We define $\mathbf{G}_{mi}$ as in (9) using downlink gains. Similar to the receive diversity case we can show that the desired signal power at the ith receiver is given by $P_i \tilde{\mathbf{W}}_i^H \mathbf{G}_{ii}^s \tilde{\mathbf{W}}_i$, and the interference power from the bth base is given by $P_b \tilde{\mathbf{W}}_b^H \mathbf{G}_{ib}^I \tilde{\mathbf{W}}_b$. The signal to noise ratio at this receiver is given by

$$\Gamma_i = \frac{P_i \tilde{\mathbf{W}}_i^H \mathbf{G}_{ii}^s \tilde{\mathbf{W}}_i}{\sum_b P_b \tilde{\mathbf{W}}_b^H \mathbf{G}_{ib}^I \tilde{\mathbf{W}}_b + \tilde{N}_i},$$

where $\tilde{N}_i$ is the thermal noise at the ith mobile, and $\mathbf{G}_{ib}^I$ is defined similar to (10). We define the transmit diversity problem as to find the power allocation and weight vectors such that the link quality is satisfied at each link. That is,

$$\Gamma_i = \gamma_i, \quad (i = 1, \ldots, M).$$

Unlike the uplink case there is no optimal power allocations and weight vectors that for a specific link quality minimize the transmitter power element-wise. This fact can be shown by a simple counter example. In the following we consider the problem of joint computation of a feasible set of combining weight vectors and power allocations. In order to achieve a feasible solution for downlink, we run the diversity combining for a virtual uplink network whose channel responses are similar to downlink, and at each iteration we use the same combining vector for the downlink. The algorithm steps at the nth iteration are as follows:

Algorithm B:

1. Diversity combining and equalization for virtual uplink:

$$\hat{\mathbf{W}}_i^n = \arg\min_{\mathbf{W}_i} \gamma_i \frac{\sum_m P_m \tilde{\mathbf{W}}_i^H \mathbf{G}_{mi}^I \tilde{\mathbf{W}}_i + \tilde{N}_i \ \tilde{\mathbf{W}}_i^H \tilde{\mathbf{W}}_i}{\tilde{\mathbf{W}}_i^H G_{ii}^s \tilde{\mathbf{W}}_i}$$

2. Virtual uplink power update:

$$\mathbf{P}^{n+1} = \mathbf{D}_w[n]\mathbf{F}_w[n]\mathbf{P}^n + \mathbf{u}_w[n],$$

3. Downlink power update:

$$\tilde{\mathbf{P}}^{n+1} = \mathbf{D}_w[n]\mathbf{F}_w^T[n]\tilde{\mathbf{P}}^n + \tilde{\mathbf{u}}_w[n],$$

where

$$\Big[\mathbf{F}_w[n]\Big]_{ij} = (\hat{\mathbf{W}}_i^n)^H \mathbf{G}_{ji}^I \hat{\mathbf{W}}_i^n, \text{ and} \qquad (14)$$

$$\mathbf{D}_w[n] = diag\{\frac{\gamma_1}{(\hat{\mathbf{W}}_1^n)^H \mathbf{G}_{11}^s \hat{\mathbf{W}}_1^n}, \ldots, \frac{\gamma_M}{(\hat{\mathbf{W}}_M^n)^H \mathbf{G}_{MM}^s \hat{\mathbf{W}}_M^n}\}, \qquad (15)$$

and the positive vectors $\mathbf{u}_w$, and $\tilde{\mathbf{u}}_w$ are defined as $\Big[\mathbf{u}_w[n]\Big]_i = \frac{\gamma_i \tilde{N}_i (\hat{\mathbf{W}}_i^n)^H \hat{\mathbf{W}}_i^n}{(\hat{\mathbf{W}}_i^n)^H \mathbf{G}_{ii}^s \hat{\mathbf{W}}_i^n}$, and $\Big[\tilde{\mathbf{u}}_w[n]\Big]_i = \frac{\gamma_i \tilde{N}_i}{(\hat{\mathbf{W}}_i^n)^H \mathbf{G}_{ii}^s \hat{\mathbf{W}}_i^n}$.

The transmitted downlink power at the ith transmitter is given by,

$$\sum_{q=0}^{Q-1} \tilde{P}_i (\hat{\mathbf{w}}_i^n)^H(q) \hat{\mathbf{w}}_i^n(q) = \tilde{P}_i (\hat{\mathbf{W}}_i^n)^H \hat{\mathbf{W}}_i^n.$$

The first two steps of the nth iteration are similar to the uplink power update equations. In [9] we have shown that in a feasible network, the second step of the algorithm B converges to a feasible power allocation ($\hat{\mathbf{P}}$). Assuming that the virtual uplink is feasible, we conclude the beamforming vectors are converging to a fixed space-time diversity vectors given by

$$\hat{\mathbf{W}}_i = \arg\min_{\mathbf{w}_i} \gamma_i \frac{\sum_m \hat{P}_m \tilde{\mathbf{W}}_i^H \mathbf{G}_{mi}^I \tilde{\mathbf{W}}_i + \tilde{N}_i \ \tilde{\mathbf{W}}_i^H \tilde{\mathbf{W}}_i}{\tilde{\mathbf{W}}_i^H G_{ii}^s \tilde{\mathbf{W}}_i}$$

As a result $\mathbf{D}_w[n]$ and $\mathbf{F}_w[n]$ are also converging to constant matrices. Since the convergence is asymptotic, the system described in algorithm B is an *asymptotically constant* system. An asymptotically constant system is asymptotically stable if the gain matrix has all its eigenvalues inside the unit circle [10]. The feasibility of virtual uplink implies that the eigenvalues of the gain matrix ($\mathbf{D}_w[n]\mathbf{F}_w[n]$) are inside the unit circle. The downlink gain matrix $\mathbf{D}_w[n]\mathbf{F}_w^T[n]$ is also converging to a fixed matrix, which has the same eigenvalues as that of the virtual uplink gain matrix [9]. Therefore the downlink is an asymptotically constant system with all its eigenvalues inside the unit circle, which implies that the downlink is also asymptotically stable. Since the feasibility of downlink and virtual uplink are the same, the algorithm will achieve the feasible solution for the downlink if there exists any.

VI. SIMULATION RESULTS

In order to evaluate the performance of our algorithm in cochannel interference reduction, a network with hexagonal cells is simulated. The path loss is proportional to r^{-4}, where r is the distance between the mobile and base station. For each link, four paths with log-normal shadow fading and Rayleigh multipath fading are considered. The angle of arrival for each path is a uniform random variable in $[0,2\pi]$. The multipath fading, and angles of arrival are also independent in uplink and downlink. We consider an FDD network with 10% frequency difference between uplink and downlink. A total of 100 mobiles, depicted by dots in Fig. 3, are distributed randomly throughout the network, and the base stations are placed at the center of each cell. Fig. 4 shows the total mobile power at each iteration. Different configurations of the equalizer length (Q) and the number of array elements (P) are considered. (P = 1, Q = 1) curve shows the case where we use omnidirectional antennas and standard power control [11]. (P = 1, Q = 4) curve shows the case where we use an equalizer with omnidirectional antenna at each base station. The solid curve shows that by using our joint space-time diversity combining and equalizers with length 4 and 9-element arrays at base stations, we can significantly reduce the total transmitted power in both uplink and downlink.

The total transmitted power in uplink and downlink as a function of the number of users is shown in Fig. 5 and 6 respectively. We define the maximum capacity of the network as the maximum number of users such that the total transmitter power is below a certain limit. The maximum capacity of the network improves significantly as we increase the number of array elements and the length of the equalizer.

VII. CONCLUSION

We have proposed algorithms for transmit and receiver space-time diversity jointly with power control, which achieves a feasible set of space-time vectors and power allocations if there exists any. The proposed algorithm guarantees the SNR at each link. We have shown that when we use adaptive arrays at the base station, using our algorithm, we can increase the uplink and downlink capacity many folds.

VIII. REFERENCES

[1] R. A. Monzingo and T. W. Miller, *Introduction to Adaptive Arrays.* New York, Wiley, 1980.

[2] P. Balaban, and J. Sulz, "Optimum combining and equalization in digital data transmission with application to cellular mobile radio," *IEEE Trans. Vehich. Tech.*, May 1991, pp. 342-354..

[3] H. Liu and G. Xu, "Multiuser Blind Channel Estimation and Spatial Channel Pre-Equalization," In *Proc. ICASSP'95"*, pp. 1756-1759, Detroit, MI, May 1995.

[4] E. Periha, G. Pottie, "Adaptive Antenna Arrays and Equalization for Indoor Digital Radio", *IEEE Int. Conf. Comm. ICC-96*, June 1996.

[5] D. Gerlach, and A. Paulraj, "Adaptive transmitting antenna array with feedback," *IEEE Sig. Proc. Lett.*, vol. 1, No. 10, Oct. 1994.

[6] G. G. Raleigh, S. D. Diggavi, V. K. Jones, and A. Paulraj, "A blind adaptive transmit antenna algorithm for wireless communications," *Proc. ICC'95*, p. 1949, vol.3, 1995.

[7] P. Zetterberg, and B. Otterson, "The spectrum efficiency of a base station antenna array system for spatially selective transmission," *IEEE Trans. Vehich. Tech.*, vol. 44, no. 3, pp. 651-660, Aug. 1995.

[8] F. Rashid-Farrokhi, L. Tassiulas, K.J.R. Liu, "Joint optimal power control and beamforming for wireless networks with antenna arrays," *Proc. IEEE Global Communications Conference (GLOBECOM-96)*, pp. I-555-559, London, Nov. 1996.

[9] F. Rashid-Farrokhi, K.J.R. Liu, L. Tassiulas, " Transmit and Receive Space-Time Diversity in Wireless Networks with Fading Channels," *ISR technical report*, Institute for System Research, University of Maryland at College Park, Sept. 1997.

[10] J. L. Willems, "Stability Theory of Dynamical Systems," John Wiley & Sons, Inc., New York, 1970.

[11] J. Zander, "Distributed cochannel interference control in cellular radio systems," *IEEE Trans. Vehicular Technol.*, vol. 41, Aug. 1992.

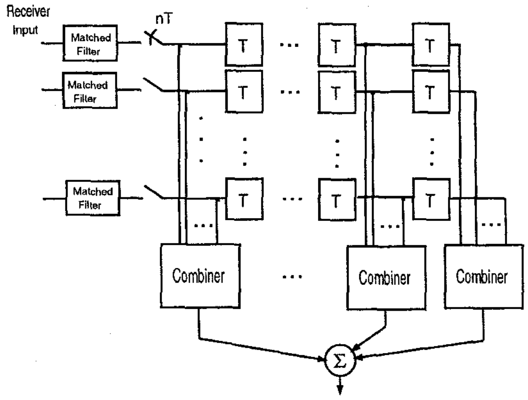

Figure 1: Block diagram of a receiver space-time combiner.

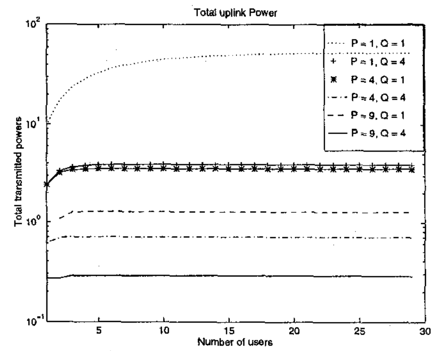

Figure 4: The total mobile powers at each iteration; 100 users and $\gamma = .03$; (P : number of array elements, Q : the length of equalizer).

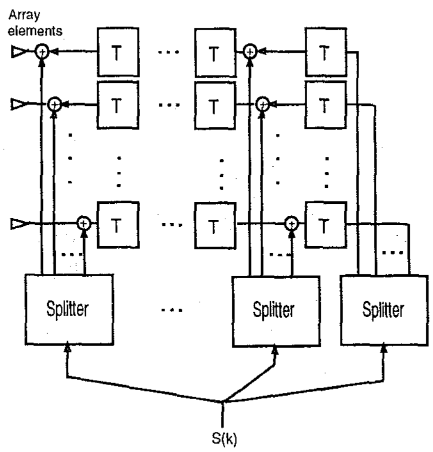

Figure 2: Block diagram of the transmit diversity system.

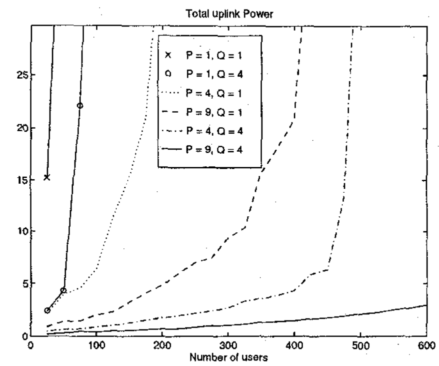

Figure 5: The total mobile powers as a function of the number of users; $\gamma = .05$.

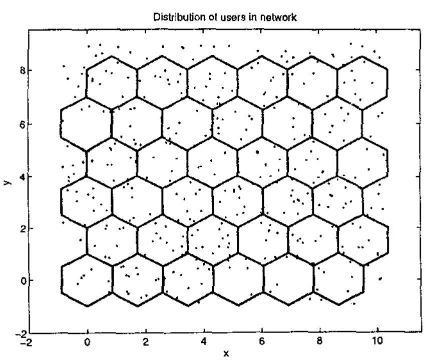

Figure 3: Mobile locations for 100 users.

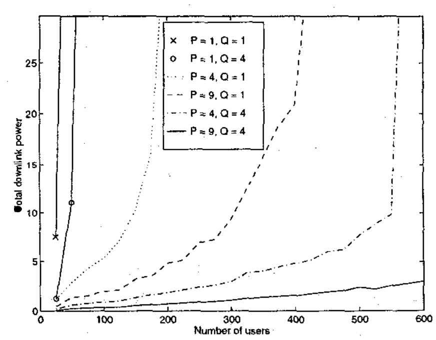

Figure 6: The total base station powers as a function of the number of users; $\gamma = .05$.