Downlink Beamforming for DS-CDMA Mobile Radio with Multimedia Services

Ying-Chang Liang[1], *Francois P.S. Chin*[1] *and K.J. Ray Liu*[2]

[1] Centre for Wireless Communications, 20 Science Park Road, #02-34/37 TeleTech Park, Singapore Science Park II, Singapore 117674
Email: cwclyc@leonis.nus.edu.sg, cwccps@leonis.nus.edu.sg

[2] Department of Electrical Engineering, University of Maryland, College Park, MD 20742
Email: kjrliu@isr.umd.edu

Abstract: Downlink beamforming is a promising technique for DS-CDMA systems with multimedia services to effectively reduce strong interferences induced by high data rate users. In this paper, we first proposed a new downlink beamforming algorithm which converts downlink beamforming problem to a virtual uplink one and takes into account of the data rate information of all users. Since the main complexity of this algorithm is due to existence of multipath effect, a simplified algorithm is suggested using equivalent one-path channel vector (EOCV) to replace multi path channel vectors. Computer simulation results are given to evaluate downlink capacity of DS-CDMA systems using base station antenna and new algorithms proposed in this paper.

I. INTRODUCTION

Wideband DS-CDMA is a promising radio access technique for the 3rd generation mobile communication systems due to its flexibility to support a variety of voice, video and data services. These services will require higher data rates and higher received signal power levels, thus creating larger interference between users. In order to obtain high system capacity, the interference levels have to be reduced effectively.

Spatial division multiple access (SDMA), by which a plurality of antenna elements are equipped at the base station in order to receive and transmit data information from and to the desired user by using spatial diversities, has been proposed as an effective technique to suppress interferences. The main operations in SDMA include uplink (from mobile station to base station) beamforming and downlink (from base station to mobile station) beamforming. Uplink beamforming is easily implemented as compared with its downlink counterpart since the antenna array is usually equipped at the base station [1,2]. However, it is also desirable to increase downlink capacity in order to improve the whole system capacity. Moreover, downlink performance is even more important for the next generation communication systems in which wireless internet, video-on-demand and multimedia services are required.

Usually, there are two issues which complicate downlink beamforming problem. First, frequency-division-duplex (FDD) mode is adopt as duplex scheme in most current wireless communication systems, and most probably will be used in the next generation systems. Second, when systems are required to provide different data rate services, traditional approaches which just keep main beam toward the desired user are not good enough, especially for the cases in which lower data rate user are spatially closed to higher data rate users.

In this paper, we evaluate downlink performance of DS-CDMA systems with base station antenna array. We consider per-user-per-path (PUPW) beamforming scheme due to its simplicity for implementation, and its robustness to path-changing problem [3]. A simple-to-use SINR expression is first derived, from which downlink beamforming problem is formulated. As it is difficult to obtain the optimal solution, we convert the downlink beamforming problem into a virtual uplink beamforming and power control problem using some approximations. A new method for generating downlink beamforming weights is proposed by considering the data rate information of all users. A simplified algorithm is also derived by using equivalent one-path channel vectors (EOCVs) to replace multipath channel vectors. Practical considerations are also given in this paper. Computer simulations were carried out to evaluate downlink capacity of DS-CDMA systems using base station antenna array together with the new beamforming techniques proposed in this paper.

II. SYSTEM DESCRIPTION

Single cell is considered in this paper. Suppose N mobile users share the same base station in which a M-element antenna array is equipped. Narrowband signals are first spread to wideband signals using different spreading codes. A 2-layered code structure which consists of short spreading codes and long scrambling codes is adopt. The scrambling codes are assigned specifically to each cell in the downlink.

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Multicode spreading scheme is used for multirate transmission. Specifically, we distinguish basic rate users and high rate users, and use equal processing gain scheme to spread them. For basic rate users, the data signal of different users are first spread by the orthogonal short spreading codes, and then summed up to be randomized by same long random sequence with the same chip rate as the orthogonal spreading sequences. For high data rate users, the data sequences are first converted to several parallel basic rate data streams, with each of which spread by different orthogonal short spreading sequences and then summed up to be randomized by the long scrambling sequence.

Suppose user k is with normalized data rate $r_d(k)$, which is the ratio of kth user's data rate to the basic data rate. Let $d_{c,k}^{(j)}(t)$ and $c_{c,k}^{(j)}(t)$ be the data signal and spreading signal of the kth user's jth code channel, respectively, and $P_{d,k}$ is the average transmitted signal power for one code channel of user k. The kth signal to be transmitted to mobile user k is given by

$$s_k(t) = \sqrt{P_{d,k}} \sum_{j=1}^{r_d(k)} d_{c,k}^{(j)}(t) c_{c,k}^{(j)}(t) \quad (1)$$

for $k = 1, \cdots, N$, with

$$d_{c,k}^{(j)}(t) = \sum_{m=-\infty}^{\infty} d_k^{(j)}(m) u\left(\frac{t}{T} - m\right)$$

$$c_{c,k}^{(j)}(t) = \sum_{m=-\infty}^{\infty} \sum_{l=0}^{G-1} f(l+mG) c_k^{(j)}(l) u\left(\frac{t}{T_c} - l - mG\right)$$

for $j = 1, \cdots, r_u(k)$, where $f(m)$, $m = \cdots, -1, 0, 1, \cdots$, represents the complex, scrambling sequences common to all users; $d_k^{(j)}(m)$, $m = \cdots, -1, 0, 1, \cdots$, and $c_k(m)$, $m = 0, \cdots, G-1$, denote the data sequence and the G-chip, complex short spreading sequence of the jth code channel of user k, respectively; T and T_c are the data symbol duration and chip duration, respectively; $u(t) = 1$ for $0 \leq t < 1$ and $u(t) = 0$ elsewhere; and $G = T/T_c$ is the processing gain. We assume that $|f(l+mG)| = |c_k^{(j)}(l)| = 1$, and $r_d(k)$ is a positive integer.

Let $\mathbf{w}_{d,j}$ denote the downlink beamforming weight vector for user j. The received signal at mobile user k is given by

$$r_k(t) = \sum_{j=1}^{N} \sum_{i=1}^{L_k} \mathbf{w}_{d,j}^H \mathbf{h}_{d,k}^{(i)} s_j(t - \tau_k^{(i)}) + n_k(t) \quad (2)$$

where L_k is the number of resolvable paths of signals received at the kth user, $\mathbf{h}_{d,k}^{(i)}$ and $\tau_k^{(i)}$ denote the downlink channel vector and time delay corresponding to the ith path of user k, respectively; and $n_k(t)$ is additive white Gaussian noise (AWGN) received at mobile k. We assume the one-sided spectrum density of the AWGNs at mobiles are all equal to N_0.

III. SIR FORMULA

For basic data rate users, the received signal is despread by using the spreading signal. For higher data rate users, several matched filters or correlators are employed in order to despread all code channels. Assume that the mobile receiver knows the exact time delays, $\tau_k^{(i)}$'s, of the multipath signals. The despread output of the lth path of the kth user's pth code channel is given by

$$z_{k,p}^{(l)}(m) = \frac{1}{T_c} \int_{mT+\tau_k^{(l)}}^{(m+1)T+\tau_k^{(l)}} r_k(t) c_{c,k}^{(p)^*}(t - \tau_k^{(l)}) dt$$

We consider L_k-finger Rake combiner using MRC, and denote the Rake coefficients as

$$\epsilon_{(j,k)}^{(i)} = \mathbf{w}_{d,j}^H \mathbf{h}_{d,k}^{(i)}$$

for $i = 1, \cdots, L_k$. The Rake combiner output is

$$z_{k,p}(m) = \sum_{l=1}^{L_k} \epsilon_{(k,k)}^{(l)\,*} z_{k,p}^{(l)}(m)$$

At the combiner output, the interference plus background noise power is given by

$$\begin{aligned} I_{d,k,p} &= G P_{d,k} r_d(k) \sum_{l=1}^{L_k} \sum_{i=1, i\neq l}^{L_k} |\epsilon_{(k,k)}^{(l)}|^2 |\epsilon_{(k,k)}^{(i)}|^2 \\ &\quad + G \sum_{j=1, j\neq k}^{N} P_{d,j} r_d(j) \left(\sum_{l=1}^{L_k} |\epsilon_{(k,k)}^{(l)}|^2 \sum_{i=1}^{L_k} |\epsilon_{(j,k)}^{(i)}|^2 \right. \\ &\quad \left. - \sum_{l=1}^{L_k} |\epsilon_{(k,k)}^{(l)}|^2 |\epsilon_{(j,k)}^{(l)}|^2 \right) + G^2 \frac{N_0}{T} \sum_{l=1}^{L_k} |\epsilon_{(k,k)}^{(l)}|^2 \end{aligned}$$

where the first and second terms of the above equation correspond to IFI and MAI, respectively, the last term is due to background noise. The instantaneous signal power of Rake combiner output is

$$S_{d,k,p} = G^2 P_{d,k} \left(\sum_{l=1}^{L_k} |\epsilon_{(k,k)}^{(l)}|^2 \right)^2$$

Note $I_{d,k,p}$ and $S_{d,k,p}$ are independent of the code channel number p, thus we omit p from them, and each code channel of user k has same instantaneous SIR, which is given by

$$SIR_{d,k} = S_{d,k} / I_{d,k}$$

Although the SIR formula is derived by assuming that the normalized data retes, $r_d(k)$'s, are positive integer, it is still satisfied when $r_d(k)$'s are positive non-integer number. The simulation results given in Section VII are based on non-integer normalized data rates.

IV. DOWNLINK BEAMFORMING – OPTIMAL SOLUTION

The above section derived the SIR formula for mobile receivers given downlink beamforming weights controlled by base station. In practice, SIR-based power control is also needed. For same SIR requirement, we try to maintain $SIR_{d,k} = \gamma_0$ for each k, where γ_0 is the target SIR threshold, or

$$(\mathbf{I} - \gamma_0 \mathbf{F}_d)\mathbf{p}_d = \gamma_0 \mathbf{g}_d \tag{3}$$

where $\mathbf{F}_d = \mathbf{DFR}$, $\mathbf{p}_d = \left[\frac{P_{d,1}T}{N_0}, \cdots, \frac{P_{d,N}T}{N_0}\right]^T$, and $\mathbf{g}_d = \left[\frac{1}{\sum_{l=1}^{L_1} |\mathbf{w}_{d,1}^H \mathbf{h}_{d,1}^{(l)}|^2}, \cdots, \frac{1}{\sum_{l=1}^{L_N} |\mathbf{w}_{d,N}^H \mathbf{h}_{d,N}^{(l)}|^2}\right]^T$ with

$$\mathbf{D} = \mathrm{diag}\left[\frac{1}{\sum_{l=1}^{L_1} |\mathbf{w}_{d,1}^H \mathbf{h}_{d,1}^{(l)}|^2}, \cdots, \frac{1}{\sum_{l=1}^{L_N} |\mathbf{w}_{d,N}^H \mathbf{h}_{d,N}^{(l)}|^2}\right]$$

$$\mathbf{R} = \mathrm{diag}[r_d(1), \cdots, r_d(N)]$$

and

$$[\mathbf{F}]_{i,j} = \begin{cases} \frac{1}{G}\left(\sum_{l=1}^{L_i} |\mathbf{w}_{d,i}^H \mathbf{h}_{d,i}^{(l)}|^2 - \frac{\sum_{l=1}^{L_i} |\mathbf{w}_{d,i}^H \mathbf{h}_{d,i}^{(l)}|^4}{\sum_{l=1}^{L_i} |\mathbf{w}_{d,i}^H \mathbf{h}_{d,i}^{(l)}|^2}\right), & \text{if } i = j \\ \frac{1}{G}\left(\sum_{l=1}^{L_i} |\mathbf{w}_{d,j}^H \mathbf{h}_{d,i}^{(l)}|^2 - \frac{\sum_{l=1}^{L_i} |\mathbf{w}_{d,i}^H \mathbf{h}_{d,i}^{(l)}|^2 |\mathbf{w}_{d,j}^H \mathbf{h}_{d,i}^{(l)}|^2}{\sum_{l=1}^{L_i} |\mathbf{w}_{d,i}^H \mathbf{h}_{d,i}^{(l)}|^2}\right), & \text{if } i \neq j \end{cases}$$

For a given set of channel responses and downlink beamforming weights, if and only if $\gamma_0 < \frac{1}{\rho(\mathbf{F}_d)}$, where $\rho(\mathbf{F}_d)$ is the spectral radius of $\mathbf{F}_d$, there exists a positive $\mathbf{p}_d = \gamma_0(\mathbf{I} - \gamma_0 \mathbf{F}_d)^{-1}\mathbf{g}_d$ such that all $SIR_{d,k}$'s are equal to γ_0. If we do not consider power constraint, $\frac{1}{\rho(\mathbf{F}_d)}$ is actually the maximum achievable SIR threshold.

If downlink channel responses and beamforming weights are known *a prior*, the above centralized power control can be used to adjust transmitted powers in order for all users to work at the given SIR requirement. In practice, however, centralized power control is too complicated for implementation, thus decentralized power control scheme based upon SIR measurement is used. Nevertheless, centralized downlink power control serves as the theoretical basis for assessing the system capacity. Especially, if the target SIR threshold is $\gamma_{d,0}$, one may define the outage probability as

$$P_{out} = \Pr\left\{\frac{1}{\rho(\mathbf{F}_d)} < \gamma_{d,0}\right\}. \tag{4}$$

Therefore, *the objective of downlink beamforming is, for given $\gamma_{d,0}$, to choose a set of beamforming weights $\mathbf{w}_{d,k}$'s, such that P_{out} is minimal, or maximum number of users can be supported within the same sector.* As P_{out} is most probably affected by the cases whose $\frac{1}{\rho(\mathbf{F}_d)}$ value is near $\gamma_{d,0}$, the objective is equivalent to find a set of weight vectors such that $\frac{1}{\rho(\mathbf{F}_d)}$ value is maximized for those cases, or generally, minimum total transmitted power, $\mathbf{1}^T\mathbf{R}\mathbf{p}_d$, is required in order to achieve the SIR threshold.

The process to obtain the above solution, which is the optimal solution, is a difficult multi-variable optimization problem, and to the best of our knowledge, there are not any efficient techniques to solve this problem. In the next section, the above problem will be converted into an easily solved problem by making some approximations.

V. DOWNLINK BEAMFORMING ALGORITHM

Since the optimal weight vector, $\mathbf{w}_{d,i}$, generates almost equal beam responses at the DOAs of all paths of user i, or $|\mathbf{w}_{d,i}^H \mathbf{h}_{d,i}^{(k)}|^2 \approx |\mathbf{w}_{d,i}^H \mathbf{h}_{d,i}^{(l)}|^2$, for $k \neq l$, $[\mathbf{F}]_{i,j}$ in $\mathbf{F}_d$ of Eq.(3) approaches

$$[\tilde{\mathbf{F}}]_{i,j} = \begin{cases} \frac{1}{G}\left(\sum_{l=1}^{L_i} |\mathbf{w}_{d,i}^H \mathbf{h}_{d,i}^{(l)}|^2 - \frac{\sum_{l=1}^{L_i} |\mathbf{w}_{d,i}^H \mathbf{h}_{d,i}^{(l)}|^4}{\sum_{l=1}^{L_i} |\mathbf{w}_{d,i}^H \mathbf{h}_{d,i}^{(l)}|^2}\right), & \text{if } i = j \\ \frac{L_i - 1}{G L_i} \sum_{l=1}^{L_i} |\mathbf{w}_{d,j}^H \mathbf{h}_{d,i}^{(l)}|^2, & \text{if } i \neq j \end{cases}$$

thus $\tilde{\mathbf{F}} \approx \mathbf{F}$, $\mathbf{D}\tilde{\mathbf{F}}\mathbf{R} \approx \mathbf{DFR}$ and $\rho(\mathbf{D}\tilde{\mathbf{F}}\mathbf{R}) \approx \rho(\mathbf{DFR})$.

Note $\rho(\mathbf{F}_d) = \rho(\mathbf{DFR}) = \rho(\mathbf{DF}^T\mathbf{R})$ since both $\mathbf{D}$ and $\mathbf{R}$ are diagonal matrices [2]. Construct $\mathbf{F}_u = \mathbf{D}\tilde{\mathbf{F}}^T\mathbf{R}$, we have $\rho(\mathbf{F}_d) \approx \rho(\mathbf{F}_u)$. By using these relations, the solution to downlink beamforming problem can be obtained by using joint *virtual* uplink beamforming and power control techniques. Here "virtual uplink beamforming" means performing virtual uplink beamforming by using downlink channel responses as virtual uplink channel responses. Using similar method in [2], we can show that the required total transmitted power, $\mathbf{1}^T\mathbf{R}\mathbf{p}_d$, is minimal in order to achieve the SIR requirement, $\gamma_{d,0}$. Below, we first outline the algorithm of virtual uplink beamforming scheme, then analyze the steps involved, finally consider some practical implementation issues.

V.A. Algorithm Steps:

The algorithm for virtual uplink beamforming and power control consists of the following steps:

- (1.1) choose an initial virtual uplink power vector;
- (1.2) compute the optimal weight vectors for given power vector;
- (1.3) compute the received power vector for given weight vectors;
- (1.4) iteratively update (1.2) and (1.3) until the power and weight vectors are converged. The converged weight vectors are used for downlink beamforming weight vectors.

V.B. Analysis of Step (1.2):

Let $\mathbf{w}_{u,k}$ be the kth user's virtual uplink beamforming weight vector, and denote the Rake combiner coefficients as

$$\epsilon_{u,k}^{(l)} = \mathbf{w}_{u,k}^H \mathbf{h}_{d,k}^{(l)} \qquad (5)$$

The MMSE solution of the virtual uplink beamforming weights is given by

$$\mathbf{w}_{u,k}^{(o)} = \mathbf{R}_k^{-1}\mathbf{r}_k \qquad (6)$$

where

$$\mathbf{R}_k = \sum_{i=1}^{L_k}\sum_{j=1}^{L_k} \epsilon_{u,k}^{(i)\,*}\epsilon_{u,k}^{(j)}\mathbf{Q}_k^{(i,j)}, \quad \text{and} \quad \mathbf{r}_k = \sum_{i=1}^{L_k}\epsilon_{u,k}^{(i)\,*}\mathbf{q}_k^{(i)} \qquad (7)$$

where

$$\begin{aligned}\mathbf{Q}_k^{(l,l)} &= r_d(k)P_{u,k}G\sum_{j\neq l}\mathbf{h}_{d,k}^{(j)}\mathbf{h}_{d,k}^{(j)\,H} \\ &+G\sum_{m\neq k}\frac{L_m-1}{L_m}r_d(m)P_{u,m}\sum_j \mathbf{h}_{d,m}^{(j)}\mathbf{h}_{d,m}^{(j)\,H} \\ &+P_{u,k}G^2\mathbf{h}_{d,k}^{(l)}\mathbf{h}_{d,k}^{(l)\,H} + \frac{N_0}{T}G^2\mathbf{I} \end{aligned} \qquad (8)$$

$$\mathbf{Q}_k^{(j,l)} = P_{u,k}G^2\mathbf{h}_{d,k}^{(j)}\mathbf{h}_{d,k}^{(l)\,H}, \quad j \neq l \qquad (9)$$

and

$$\mathbf{q}_k^{(i)} = \sqrt{P_{u,k}}G\mathbf{h}_{u,k}^{(i)} \qquad (10)$$

Based on Eqs.(5)-(10), an iterative approach can be developed for estimating the optimum virtual uplink beamforming weights for given power vector.

- (2.1) choose an initial virtual weight vector; say $\mathbf{w}_{u,k} = [1, 0, \cdots, 0]^T$;
- (2.2) using Eq.(5) to calculate the virtual Rake combiner coefficients;
- (2.3) compute $\mathbf{R}_k$ and $\mathbf{r}_k$ from Eqs.(7) - (10), thus the virtual weight vector from Eq.(8);
- (2.4) iteratively update (2.2) and (2.3) until the weight vector is converged.

V.C. Analysis of Step (1.3):

With optimal virtual beamforming weights in hand, the virtual uplink SIR formula can be shown as follows:

$$SIR_{u,k} = \frac{\frac{P_{u,k}T}{N_0}}{\sum_{i=1}^{N} f_{k,i}\frac{P_{u,i}T}{N_0} + \frac{||\mathbf{w}_{u,k}||^2}{\sum_{l=1}^{L_k}|\mathbf{w}_{u,k}^H\mathbf{h}_{d,k}^{(l)}|^2}} \qquad (11)$$

with

$$f_{k,i} = \begin{cases} \frac{r_d(k)}{G}\left(1 - \frac{\sum_{l=1}^{L_k}|\mathbf{w}_{u,k}^H\mathbf{h}_{d,k}^{(l)}|^4}{\left(\sum_{l=1}^{L_k}|\mathbf{w}_{u,k}^H\mathbf{h}_{d,k}^{(l)}|^2\right)^2}\right) & \text{if} \quad i = k \\ \frac{(L_i-1)r_d(i)}{L_iG}\frac{\sum_{l=1}^{L_i}|\mathbf{w}_{u,k}^H\mathbf{h}_{d,i}^{(l)}|^2}{\sum_{l=1}^{L_k}|\mathbf{w}_{u,k}^H\mathbf{h}_{d,k}^{(l)}|^2} & \text{if} \quad i \neq k \end{cases}$$

for $k = 1, \cdots, N$. Using SIR-based power control, we try to adjust the virtual transmitted powers such that the SIR at the virtual Rake combiner output is always kept at the prescribed target value $\gamma_{u,0}$ for each user, while each transmitter keeps the transmitted power at the minimum required level to reduce the interference to other users, or we try to keep

$$(\mathbf{I} - \gamma_{u,0}\mathbf{F}_u)\mathbf{p}_u = \gamma_{u,0}\mathbf{g}_u \qquad (12)$$

where $[\mathbf{F}_u]_{i,j} = f_{i,j}$, $\mathbf{p}_u = \left[\frac{P_{u,1}T}{N_0}, \cdots, \frac{P_{u,N}T}{N_0}\right]^T$, and $\mathbf{g}_u = \left[\frac{||\mathbf{w}_{d,1}||^2}{\sum_{l=1}^{L_1}|\mathbf{w}_{d,1}^H\mathbf{h}_{d,1}^{(l)}|^2}, \cdots, \frac{||\mathbf{w}_{d,N}||^2}{\sum_{l=1}^{L_N}|\mathbf{w}_{d,N}^H\mathbf{h}_{d,N}^{(l)}|^2}\right]^T$. Given a set of virtual uplink beamforming weights, $\mathbf{w}_{u,k}$'s, if and only if $\gamma_{u,0} < \frac{1}{\rho(\mathbf{F}_u)}$, there exists a positive power vector, $\mathbf{p}_u = (\mathbf{I} - \gamma_{u,0}\mathbf{F}_u)^{-1}\gamma_{u,0}\mathbf{g}_u$, such that $SIR_{u,k}$'s are all equal to $\gamma_{u,0}$, while each element of the transmitted power vector is minimized.

V.D. Some Considerations:

(1) The above algorithm, called Algorithm A, takes into account downlink data rate information in designing downlink beamforming weights, thus can be considered as a multi-rate extention of the algorithm proposed in [2].

(2) In the iterative process, we choose $\gamma_{u,0} = \gamma_{d,0}$ for $\gamma_{d,0} < \frac{1}{\rho(\mathbf{F}_u)}$, and $\gamma_{u,0} = \frac{0.9}{\rho(\mathbf{F}_u)}$ for $\gamma_{d,0} >= \frac{1}{\rho(\mathbf{F}_u)}$, where $\gamma_{u,0}$ is the target SINR threshold in the virtual uplink update.

(3)Uplink channel estimates are used as downlink channel responses for TDD mode; while for FDD mode, further frequency calibration is required [4].

(4) Since downlink beamforming weights are generated *a prior*, once the they are generated, downlink power control can be implemented via fast transmit power control scheme [5].

VI. A SIMPLIFIED ALGORITHM

In virtual uplink beamforming, it is the multi delay effect that makes it complicated to obtain virtual uplink weight vectors for given virtual uplink power vector. In fact, if there is only one path, a one-step closed form solution exists. Base on this idea, for multi delay case, Algorithm B generates an equivalent one-path channel vectors (EOCVs) to reduce the complexity of the involved algorithm.

Denote $\tilde{\mathbf{h}}_{d,k}$ as the EOCV of user k, and $\tilde{\mathbf{w}}_{d,k}$ as the virtual uplink beamforming weight vector of user k. Let $\epsilon_{u,k} = \tilde{\mathbf{w}}_{u,k}^H\tilde{\mathbf{h}}_{d,k}$. From Eqns.(5)-(10), the MMSE solution of the virtual uplink beamforming weights is given by

$$\tilde{\mathbf{w}}_{u,k}^{(o)} = \tilde{\mathbf{R}}_k^{-1}\tilde{\mathbf{r}}_k \qquad (13)$$

where $\tilde{\mathbf{R}}_k = ||\epsilon_{u,k}||^2\mathbf{Q}_k$ and $\tilde{\mathbf{r}}_k = \epsilon_{u,k}^*\mathbf{q}_k$ with

$$\begin{aligned}\mathbf{Q}_k &= G\sum_{m\neq k}\frac{L_m-1}{L_m}r_d(m)P_{u,m}\tilde{\mathbf{h}}_{d,m}\tilde{\mathbf{h}}_{d,m}^H \\ &+P_{u,k}G^2\tilde{\mathbf{h}}_{d,k}\tilde{\mathbf{h}}_{d,k}^H + \frac{N_0}{T}G^2\mathbf{I}\end{aligned} \qquad (14)$$

and

$$\mathbf{q}_k = \sqrt{P_{u,k}} G \tilde{\mathbf{h}}_{u,k} \quad (15)$$

The EOCV can be estimated by choosing the principal eigenvector of the user's downlink channel covariance matrix (DCCM), which is defined

$$\mathbf{R}_{d,k} = [\mathbf{h}_{d,k}^{(1)}, \cdots, \mathbf{h}_{d,k}^{(L_k)}][\mathbf{h}_{d,k}^{(1)}, \cdots, \mathbf{h}_{d,k}^{(L_k)}]^H$$

for $k = 1, \cdots, N$. The DCCM is same as the uplink channel covariance matrix (UCCM) for TDD mode; while for FDD mode, DCCM can be estimated from UCCM using frequency calibration processing [4].

VII. COMPUTER SIMULATIONS AND CONCLUSIONS

A 6-element ULA is equipped at the base station for each sector (3 sectors per cell). Consecutive antennas are spaced at half uplink wavelength. Single cell capacity is evaluated for both TDD ($f_u = f_d = 1.8$GHz) and FDD ($f_u = 1.8$GHz, $f_d = 2.0$GHz) duplex modes. Macrocell systems are considered in which the angular separation between each delay path of the same user is within 10^o, and the angular spread for each delay path is 1^o. Each user is with 2 delay paths (Rayleigh fading) and the processing gain is $G = 16$. The SIR threshold is chosen to be $\gamma_{d,0} = 6.8$dB. We compare *Algorithm B* with maximum transmit SINR criterion (MTSINR) (MTSINR is a simplified case of Algorithm B in which $\mathbf{p}_u = [1, \cdots, 1]^T$ in Eq.(12)), D-MRC (uplink MRC weights for downlink), and FC-MRC (uplink MRC weights with frequency calibration for downlink, FDD case). Uplink data rates are randomly chosen from $\{0.1, 0.2, \cdots, 1.0\}$ with total data rate $\sum_{i=1}^{N} r_u(i) = 0.5N$, while downlink data rates are from $\{0.2, 0.4, \cdots, 2.0\}$ with $\sum_{i=1}^{N} r_d(i) = N$.

Fig.1 shows the outage probability with respect to different number of users (equals to the downlink total data rate) for TDD systems. It is seen that the performance of Algorithm B is much better than those of D-MRC and MTSINR. Specifically, for $P_{out} = 0.01$, the total data rate supported by Algorithm B is 36, while those by MTSINR and D-MRC are 28 and 23, respectively.

Fig.2 shows the results obtained for FDD systems. The total data rates supported by Algorithm B and MTSINR are 29 and 27, respectively, while those by D-MRC and FC-MRC are 22 and 23, respectively. It is evident that Algorithm B is the best among the algorithms compared.

As a conclusion, when a 6-element ULA is equipped at the base station, our new algorithm provides $\frac{36-23}{16} = 81\%$ higher capacity than D-MRC method for TDD; while for FDD, $\frac{29-22}{16} = 44\%$ higher capacity is obtained.

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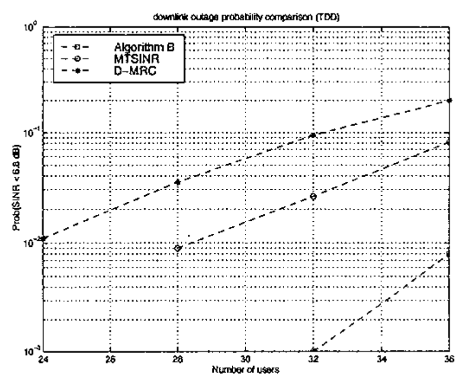

Figure 1: Outage probability of different algorithms with respect to number of users for TDD systems

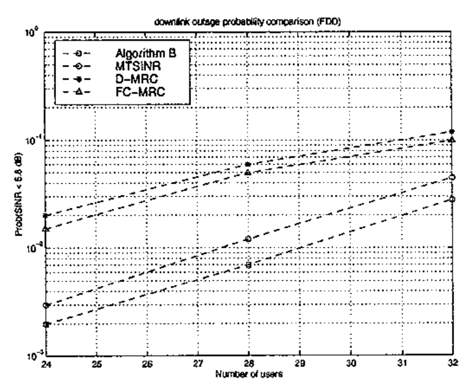

Figure 2: Outage probability of different algorithms with respect to number of users for FDD systems