# POWER CONTROL FOR DIVERSITY RECEPTION IN TIME-DIVISION DUPLEX CDMA

Irfan Ghauri*
Mobile Communications Dept.
Institut Eurécom, 2229 Route des Crêtes
06904 Sophia Antipolis Cedex, France
ghauri @eurecom.fr

Raymond Knopp
Audio Visual Communications Lab.
École Polytechnique Fédérale de Lausanne
CH-1015 Lausanne, Switzerland
knopp @lcavsun1.epfl.ch

**Abstract** Power control possiblities are explored for the downlink of a Time-Division Duplex (TDD) CDMA system while employing three different kinds of multipath diversity combining schemes namely the RAKE, the pre-RAKE [2] and the transmit antenna pre-selection. In the latter two, knowledge of the channel characterstics is employed at the base-station to provide maximum decoupling between users on the downlink. Performance of the these receivers is compared in a Rayleigh fading urban environment. It is shown that power control is absolutely indispensible in the latter two schemes and results in considerable performance gains as compared to the RAKE receiver.

## I. INTRODUCTION

The conventional receiver for DS-CDMA systems is known to be plagued by the *near-far* problem. To enable diversity reception, the RAKE receiver [6] is usually employed leading to coherent combination of multipath signals. However, not only does the RAKE combine delayed replicas of desired signal but also the coherent interference present in the system due to spreading codes with finite cross-correlations instead of being perfectly orthogonal. This instigates the need for antenna sectorization, voice activity, and power control in cellular CDMA based systems as measures for providing further immunity against interference.

Downlink power control has received considerably lesser attention as compared to its uplink counterpart owing to the fact that the existing of a pilot-tone renders power estimation easy. Furthermore, in an frequency-division duplex (FDD) case, a closed-loop implementation is required which enables the base-station to send power control information to mobile users [8]. However, in a multicellular environment, downlink power control reduces co-channel interference and thus results in an increase in the overall capacity of the system. Power control in a multicellular scenario is studied in [1] [9] and deployment methods are discussed. It is imagined that in a single isolated cell, since the signal power arriving at a user and the interference follow the same downlink path, the power assignment at the base-station is already fair. While this is true for the RAKE receiver, other diversity combining techniques might require some downlink control.

For reasonably small cell dimensions, it is fair to suppose that the channel for each user does not change over two successive TDD slots. This way, all the payload for channel estimation can be transferred to the uplink where high complexity signal and array processing techniques [5] (and references therein) can more easily be implemented. A pre-distorted signal is then transmitted on the downlink. This signal is referred to as the *pre-raked* signal in the literature for obvious reasons. At the mobile station, a single matched filter can be employed to tune to the strong peak obtained as a result of the convolution of this pre-raked signal with the channel response. This arrangement provides better performance than the RAKE since coherent combination of interfering signals is avoided. Furthermore, open-loop power control is possible on the downlink[2].

Another method investigated in this paper employs multiple antennas at the cell site. Path gains for all antennas are estimated on the uplink and the downlink signal, in the subsequent TDD slot, is transmitted only on the antennas with significant path gains.

Two types of power control can usually be exercised depending upon how frequently the channel changes over time. One is the so called slow power control accounting for the slowly evolving characterstics like the effects of shadowing and path losses. Fast power control, on the other hand, attempts to follow the rapidly varying parameters of the channel. We shall concentrate on fast power control in this paper.

In the following section, we discuss the channel characterstics of a typical mobile communication system operating in an urban environment. Fading and path-loss models are described for a DS-CDMA system like the IS-95. Data models for the three receivers are described in section III. In section IV, the power control problem is analyzed for the pre-RAKE and the pre-selection diversity case and comparisons with the classical RAKE receiver are made. Subsequently, simulation results are presented to compare the performances of the three schemes.

## II. CHANNEL CHARCTERSTICS

While describing the channel model two kinds of behaviors are of particular interest in terms of the power received by the re-

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channel, englobing the mean path-loss ($n$th power loss with distance) and the variations about the mean accounting for shadowing of the receiver by prominent terrain contours (buildings etc. in an urban milieu). Shadowing is statistically characterized as a log-normally distributed random variable. If $P_m$, where $m = 1, \cdots, K$ is the power transmitted to the $m$th mobile situated at a distance $d_m$ from the base-station, then the received power is given by $R_{m,dB} = P_{m,dB} - A_{m,dB}$, where, $A_{m,dB} = A_m(d_0)_{dB} + 10log_{10}(\frac{d_m}{d_0}) + G_\sigma$ where, $G_\sigma$ denotes a zero-mean Gaussian random variable (in dB) with standard deviation, $\sigma$ (also in dB, ≈6-10 dB). The large-scale fading mechanism is surroundings and distance dependent, i.e., even for vehicles moving at high speeds, the variation over time is rather slow. $A_m(d_0)_{dB}$ is the free-space path-loss at a reference distance $d_0$ somewhere close to the transmitting antenna [4].

The other effect is the one of *small-scale* fading which manifests itself as rapid changes in amplitude and phase of the received signal. These variations are the result of a large number of multipath components with uniformly distributed phases adding up over time (Rayleigh fading). The worst case variations can be of the order of 20-30 dB. Of course, these variations are carrier frequency dependent and their rapidity, for the system under consideration, depends upon the transmission rate and relative speeds (Doppler effect) of the transmitter and the mobile unit. In the IS-95 standard, the transmitted signal for each user is wideband compared to the coherence bandwidth of the channel, resulting in multipath components that fade independently of each other thus resulting in multipath diversity exploited by the RAKE receiver. Since the channel is frequency selective, intersymbol interference (ISI) is there but its effect is small owing to low average out-of-phase correlation of the spreading sequences. On the other hand, the transmission rate is such that the symbol duration, $T_s$, is much smaller as compared to the coherence time, $T_0$ of the channel ($\approx 5ms.$ at 75 mph. for a mobile user at a carrier frequency of 900 MHz). The variations of the channel are therefore slow as compared to the symbol rate and we can classify the process as slow fading. The fading rate of the channel gives a measure of how often the power control needs to be exercised.

## III. SYSTEM MODEL

The uplink channel impulse response of the $m$th user is written as

$$h_m(t) = \sum_{l=0}^{L-1} \alpha_{m,l} e^{j\beta_{m,l}} \delta(t - d_l - \tau_m), \tag{1}$$

where, $L$ is the number of resolvable paths, $\alpha_{m,l}$ are zero-mean circular Gaussian random variables, and $\beta_{m,l}$ is the independent uniformly distributed phase of the $l$th path of the $m$th user. The channel envelopes therefore, follow a Rayleigh pdf. $d_l$ is the delay (within the delay profile) of the $l$th path. The $\tau_m$'s account for the asynchronous nature of the uplink. On the downlink on the other hand, the channel for all users will be the same and $\tau_m = 0, \forall m$.

We consider a BPSK signal for the downlink path of mobile cellular system with $K$ users. The equivalent baseband $m$th user transmitted signal at the base station is given by

$$s_m(t) = \sqrt{P} a_m(t) c_m(t), \tag{2}$$

where, $a_m(t)$ is the transmitted symbol of the $m$th user, $c_m(t)$ is the corresponding signature waveform, and $P$ is the transmitted power, considered to be the same for all users. Let the $k$th user be the user of interest. Then the received continuous time signal at the mobile user is

$$r_k(t) = \sum_{m=1}^{K} \sum_{l=0}^{L-1} \sqrt{P} \alpha_{k,l} a_m(t - d_l) c_m(t - d_l) e^{j\beta_{k,l}} + z(t), \tag{3}$$

where, $z(t)$ is the additive noise of the channel. In each receiver, we match filter with $h_m^*(-t) * c_m(-t)$ so that the discrete-time sampled signal can be written as follows:

$$r_k(n) = \sqrt{P} a_k(n) \sum_{p=0}^{L-1} \sum_{l=0}^{L-1} \alpha_{k,p}^H \alpha_{k,l} \gamma_{k,k}(\delta_{p,l}) + \sqrt{P} \sum_{m \neq k}^{K} a_m(n) \\ \sum_{p=0}^{L-1} \sum_{l=0}^{L-1} \alpha_{k,p}^H \alpha_{k,l} \gamma_{k,m}(\delta_{p,l}) + \sum_{p=0}^{L-1} \sum_{l=0}^{L-1} \sqrt{\alpha_{k,p}^H \gamma_{kk}(\delta_{p,l}) \alpha_{k,l}} z(n), \tag{4}$$

where, $\gamma_{i,j}(\delta_{p,l})$ are the cross-correlations of the $p$- and $l$-delayed versions of spreading codes of $i$ and $j$th users. We can further write as $\boldsymbol{\alpha}_m = \left[ \begin{array}{c} \alpha_{m,1}^H \alpha_{m,2}^H \ldots \alpha_{m,L}^H \end{array} \right]^H$, and

$$\mathsf{R}_{ij} = \begin{bmatrix} \gamma_{i,j}(\delta_{1,1}) & \gamma_{i,j}(\delta_{1,2}) & \cdots & \gamma_{i,j}(\delta_{1,L}) \\ \gamma_{i,j}(\delta_{2,1}) & \gamma_{i,j}(\delta_{2,2}) & \cdots & \gamma_{i,j}(\delta_{2,L}) \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{i,j}(\delta_{L,1}) & \gamma_{i,j}(\delta_{L,2}) & \cdots & \gamma_{i,j}(\delta_{L,L}) \end{bmatrix}, \tag{5}$$

where, the matrix $\mathsf{R}_{ij}$ contains the cross-correlations of delayed versions of $i$th and $j$th user spreading codes. In a more concise fashion, the $k$th user received signal is written as

$$r_k(n) = \sqrt{P} a_k(n) \boldsymbol{\alpha}_k^H \mathsf{R}_{kk} \boldsymbol{\alpha}_k + \\ \sqrt{P} \sum_{m \neq k}^{K} a_m(n) \boldsymbol{\alpha}_k^H \mathsf{R}_{km} \boldsymbol{\alpha}_k + \sqrt{\boldsymbol{\alpha}_k^H \mathsf{R}_{kk} \boldsymbol{\alpha}_k} z(n). \tag{6}$$

We shall investigate the bit-error probability performance of the RAKE receiver in a later section.

### *B. Pre-RAKE Receiver*

For the pre-RAKE case, it is assumed that perfect estimate of the channel has already been obtained during the course of the previous uplink time slot of the time-division duplex. The $m$th user transmitted signal at the base station is given by

$$s_m(t) = \sqrt{P} a_m(t) c_m(t) * h_m^*(-t). \tag{7}$$

In eq. (7), it can be seen that the power transmitted for each user is variable (of unit-mean) as a function of its channel.

$$r_k(t)=\sum_{m=1}^{K}\sum_{l=0}^{L-1}\sum_{p=0}^{L-1}\sqrt{P}\alpha_{m,L-l-1}\alpha_{k,p}a_m(t-d_l-p) \\ c_m(t-d_l-p)e^{j(\beta_{m,L-l-1}-\beta_{k,p})}+z(t). \tag{8}$$

$r_k(t)$ is passed through the desired user code matched filter and sampled at the symbol rate. The $n$th instant discrete-time received signal at the mobile station is then written as

$$\begin{aligned} r_k(n) &= \sqrt{P}a_k(n)\sum_{p=0}^{L-1}\sum_{l=0}^{L-1}\alpha_{k,p}^{H}\alpha_{k,l}\gamma_{k,k}(\delta_{p,l}) + \\ &\sqrt{P}\sum_{m\neq k}^{K}a_m(n)\sum_{p=0}^{L-1}\sum_{l=0}^{L-1}\alpha_{k,p}^{H}\alpha_{m,l}\gamma_{k,m}(\delta_{p,l}) + z(n), \end{aligned} \tag{9}$$

or,

$$\begin{aligned} r_k(n) &= \sqrt{P}a_k(n)\boldsymbol{\alpha}_k^H\mathsf{R}_{kk}\boldsymbol{\alpha}_k \\ &+\sqrt{P}\sum_{m\neq k}^{K}a_m(n)\boldsymbol{\alpha}_k^H\mathsf{R}_{km}\boldsymbol{\alpha}_m^H + z(n). \end{aligned} \tag{10}$$

### C. Pre-Selection Diversity

Let us consider multiple antennas at the base-station of a cell. Since the mobile stations are uniformly distributed in an approximate circle around the cell site, the uplink paths for each of them are independent. Moreover, if the antennas are located sufficiently seperated from each other, they would receive fairly uncorrelated multipath signals from the same user. This means that a particular antenna on the base-station might be a strong-signal recipient for a certain number of users at a particular time instant. In the next slot of the TDD, the signal on the downlink is transmitted only from the antennas which represent strong paths for the user in question. While doing so, the interference to other users is diminished. This arrangement is somewhat analogous to the concept of antenna sectorization since mobile users are assigned groups corresponding to indices of their respective strongest paths. Let $h_{q,k}(t)$, where $q=1\ldots Q$, be the attenuation factors of the $q$th base station antenna for the $k$th user, the one of interest. Then, if $h_{i,k}(t)$ represents by far the most dominant channel (in terms of attenuation), the signal is transmitted only from this antenna:$i$ on the downlink for the $k$th user. Furthermore, $K_q$ is the number of users with the $q$th antenna as their strongest signal path, and $P_{qk}$ is the transmitted power from the $q$th antenna to the $k$th user. The down-converted and sampled discrete-time received signal at the $k$th user is

$$\begin{aligned} r_k(t) &= \sqrt{P_{ik}}a_k(n)\boldsymbol{\alpha}_{i,k}^H\mathsf{R}_{kk}\boldsymbol{\alpha}_{i,k} \\ &+\sum_{q=1}^{Q}\sum_{m\neq k}^{K_q}\sqrt{P_{qm}}a_m(n)\boldsymbol{\alpha}_{q,k}^H\mathsf{R}_{km}\boldsymbol{\alpha}_{q,k} + z(n), \end{aligned} \tag{11}$$

where, $\boldsymbol{\alpha}_{q,m}$ is the vector of gains (amplitudes) of the multipath channel between the $q$th antenna and the $m$th user, and $\mathsf{R}_{m,k}$ are the same as defined in eq. (5) as the correlations of the $m$th and $k$th user codes. The pre-selection is based upon the 2-norm of

$$\Gamma = \frac{2E_bP_{ik}(\boldsymbol{\alpha}_{i,k}^H\mathsf{R}_{kk}\boldsymbol{\alpha}_{i,k})^2}{N_o+2E_b\sum_{q=1}^{Q}\sum_{m=\neq k}^{K_q}P_{q,m}(\boldsymbol{\alpha}_{q,k}^H\mathsf{R}_{km}\boldsymbol{\alpha}_{q,k})^2}, \tag{12}$$

where, $E_b$ is the energy per bit and $N_0$ is the double-sided noise power spectral density [6].

It is clear that the performance will depend on the transmitted powers of users as well as the strengths of the paths from interfereing antennas to the desired user. In the following section we shall give the expression for the optimal power $P_{im}$ transmitted for the $m$th user, so that the signal to interference ratio for each is similar.

## IV. POWER CONTROL

Power control is crucial in cellular CDMA especially on the uplink where the signals from all users should arrive with equal powers. The downlink power control is much less critical [8] in a RAKE receiver based IS-95 type system, since a pilot signal is continuously transmitted on the downlink in order to estimate the channel. On the other hand, for the other two systems, mobile stations neither need to estimate the channel co-efficients, nor do they need to track the multipath components. Only a single matched filter is required to tune to the strong peak of the pre-distorted/pre-selected signal. Therefore, some sort of power control needs to be exercised on the downlink in order to avoid swamping out of the desired signal by the interferers. In order to do this, however, the channels/path-strengths needs to be known (estimated) *a priori* at the base-station.

### A. RAKE Receiver

The desired signal and the interferers share the same channel on the downlink. It suffices, therefore to increase the power of all the users equally in order to service the weakest user. In the case of no power control, the signal-to-interference ratio at the mobile station will always stay the same, i.e.,

$$\Gamma = \frac{2PE_b(\boldsymbol{\alpha}_k^H\mathsf{R}_{kk}\boldsymbol{\alpha}_k)^2}{\boldsymbol{\alpha}_k^H\mathsf{R}_{kk}\boldsymbol{\alpha}_kN_o+2PE_b\sum_{m\neq k}^{K}(\boldsymbol{\alpha}_k^H\mathsf{R}_{km}\boldsymbol{\alpha}_k)^2}. \tag{13}$$

Then, invoking the Gaussian assumption for multiuser interference [7], and considering the transmitted symbols $a_m$ as *i.i.d.*, the probability of error for antipodal signals, conditioned on the $\alpha_{i,j}$'s is given by

$$P_{e|\alpha_{i,j}} = Q(\sqrt{2\Gamma}). \tag{14}$$

where, $Q(z)=\int_x^\infty e^{-z^2}dz$. However if we apply power control based only on the desired user's signal, then we can write the transmitted power from the $k$th user as

$$P_k = \frac{\Upsilon}{\boldsymbol{\alpha}_k^H\mathsf{R}_{k,k}\boldsymbol{\alpha}_k}, \tag{15}$$

where, $\Upsilon$ is a constant taken to be the same for all users. The SINR at the desired user is

$$\Gamma = \frac{2\Upsilon E_b}{N_o+\frac{2\Upsilon E_b}{\boldsymbol{\alpha}_k\mathsf{R}_{kk}\boldsymbol{\alpha}_k}\sum_{m\neq k}^{K}\frac{(\boldsymbol{\alpha}_k^H\mathsf{R}_{km}\boldsymbol{\alpha}_k)^2}{\boldsymbol{\alpha}_m^H\mathsf{R}_{mm}\boldsymbol{\alpha}_m}}. \tag{16}$$

We consider the following three cases for the pre-RAKE receiver.

*1) No power control*

Let us first investigate the case without any power control. This is like transmitting $s_m(t) = \sqrt{P} a_m(t) c_m(t) * h_m^*(-t)$, on the downlink for the $m$th user. The received SINR yielded is:

$$\Gamma = \frac{2PE_b(\boldsymbol{\alpha}_k^H \mathsf{R}_{kk} \boldsymbol{\alpha}_k)^2}{N_0 + 2PE_b \sum_{m \neq k}^{K} (Re\left\{\boldsymbol{\alpha}_k^H \mathsf{R}_{km} \boldsymbol{\alpha}_m\right\})^2}, \tag{17}$$

Looking at eq. (17), we observe that if the channel for the user of interest is weak, compared to the others, the performance of the receiver will be poor. In such a case, power transmitted on the downlink to the desired user must be stepped up. Likewise, powers for other users must also be controlled to be only enough for an acceptable performance. In the above, $\boldsymbol{\alpha}_m$ and the matrix $\mathsf{R}_{ij}$ are the same as defined previously in eq.(5) and $Re\left\{\cdot\right\}$ stands for the real part.

*2) Constant transmitted power*

Second, we have constant transmit power at the base station. The transmitted signal is $s_m(t) = \sqrt{P} a_m(t) c_m(t) * h_m^*(-t)/\sqrt{\boldsymbol{\alpha}_m^H \boldsymbol{\alpha}_m}$, and the received discrete-time signal is

$$\begin{aligned} r_k(n) = {} & \sqrt{P} a_m(n) \boldsymbol{\alpha}_k^H \mathsf{R}_{kk} \boldsymbol{\alpha}_k / \sqrt{\boldsymbol{\alpha}_k^H \boldsymbol{\alpha}_k} + \\ & \sqrt{P} \sum_{m \neq k}^{K} a_m(n) \boldsymbol{\alpha}_k^H \mathsf{R}_{km} \boldsymbol{\alpha}_m / \sqrt{\boldsymbol{\alpha}_m^H \boldsymbol{\alpha}_m} + z(n), \end{aligned} \tag{18}$$

The signal-to-interference ratio at user $k$, is given by

$$\Gamma = \frac{2PE_b(\boldsymbol{\alpha}_k^H \mathsf{R}_{kk} \boldsymbol{\alpha}_k)^2 / (\boldsymbol{\alpha}_k^H \boldsymbol{\alpha}_k)}{N_0 + 2PE_b \sum_{m \neq k}^{K} \frac{(Re\left\{\boldsymbol{\alpha}_k^H \mathsf{R}_{km} \boldsymbol{\alpha}_m\right\})^2}{\boldsymbol{\alpha}_m^H \boldsymbol{\alpha}_m}}, \tag{19}$$

*3) With power control*

The transmitted signal on the downlink for the $m$th user is $s_m(t) = \sqrt{P} a_m(t) c_m(t) * h_m^*(-t)/(\boldsymbol{\alpha}_m^H \mathsf{R}_{mm} \boldsymbol{\alpha}_m)$, yielding the SINR

$$\Gamma = \frac{2\Upsilon E_b}{N_0 + 2\Upsilon E_b \sum_{m \neq k}^{K} \left(Re\left\{\frac{\boldsymbol{\alpha}_k^H \mathsf{R}_{km} \boldsymbol{\alpha}_m}{\boldsymbol{\alpha}_m^H \mathsf{R}_{mm} \boldsymbol{\alpha}_m}\right\}\right)^2}. \tag{20}$$

It is seen that the effect, whether strong or weak, of the undesired multipath channel, i.e., that of an interferer is removed and fast variations (as fast as they can be estimated) can be dealt with. As we shall see later, the performance of this receiver is the best among the three pre-RAKE configurations.

### *C. Pre-selection Diversity*

From eq.(12), it is easy to see that in the event of equal signal to interference ratio for all users entertained by the base station

$$P_{ik} = \Upsilon \left( \frac{\sum_{q=1}^{Q} \sum_{m=1}^{K_q} P_{qm} (\boldsymbol{\alpha}_{q,k}^H \mathsf{R}_{km} \boldsymbol{\alpha}_{q,k})^2}{(\boldsymbol{\alpha}_{i,k}^H \mathsf{R}_{kk} \boldsymbol{\alpha}_{i,k})^2} \right), \tag{21}$$

where, $\Upsilon$ is a constant. The above equation implies that the optimal transmitted power on the downlink antenna $i$ of the $k$th user is proportional to the ratio of the total power received by this mobile and the path gain. The role of spreading sequences in the shape of $\mathsf{R}_{km}$'s, the cross-correlations between the $k$ and $m$th user spreading sequences is also explicitly seen.

Let the trasmitted power $\sum_m P_{qm} = G_q$ from the $q$th antenna be fixed for any time, as a function of the number of mobile users taken care of by this antenna. Then, the optimal power transmitted on the $i$th antenna for the $k$th user is expressed as

$$P_{ik} = G_i \left( \frac{\sum_{q=1}^{Q} G_q \left(Re\left\{\boldsymbol{\alpha}_{q,k}^H \mathsf{R}_{km} \boldsymbol{\alpha}_{q,k} / \boldsymbol{\alpha}_{i,k}^H \mathsf{R}_{kk} \boldsymbol{\alpha}_{i,k}\right\}\right)^2}{\sum_{n}^{K_i} \sum_{q=1}^{Q} G_q \left(Re\left\{\boldsymbol{\alpha}_{q,n}^H \mathsf{R}_{nm} \boldsymbol{\alpha}_{q,n} / \boldsymbol{\alpha}_{i,n}^H \mathsf{R}_{nn} \boldsymbol{\alpha}_{i,n}\right\}\right)^2} \right), \tag{22}$$

where $n$ indexes the $K_i$ users with the $i$th antenna as their downlink station. From this equation, it is seen that all users affiliated with a particular antenna will have an approximately equal received SINR. Since the distribution of users with respect to these antennas is uniform, the performance evaluated from eq.(12), for all *clusters* of users will, in general, be the same.

## V. SIMULATIONS

A series of Monte Carlo runs were carried out to compare the performance of the three diversity reception schemes. Random sequences were employed as spreading codes. The channel used depicted a typical urban scenario with either six or twelve taps[3] and a mean delay spread of 5 microseconds. Shadowing is implemented as a log-normal random variable with a variance of 8.5 dB. A carrier frequency of 900 MHz. is taken conform with the existing mobile communication norms. As a worst case, vehicular speeds of 75 mph. are considered which corresponds to a channel coherence time of approximately 5 ms. ($\approx$ 50 symbol periods at a data rate of 9.6 kb/s). Therefore, the channel can be considered to be reasonably slow fading.

Fig.1 shows the bit-error rate curves for the three receivers with 20 mobile users. The channel used for this plot is urban 6 tap. It is seen that the pre-RAKE outperforms the RAKE receiver when the power control normalizations described in section IV are introduced. Otherwise the overall performance suffers due to the cases where the channel for the users of interest is weak compared to those of the interferers. Similar results are plotted for an urban channel with 12 taps in fig.2 for the same delay spread. The overall performance for the pre-RAKE receiver would however depend upon the accuracy of power estimates on the uplink. The performance of the pre-selected transmit antenna is also presented in these figures. Curves for that a significant improvement is obtained by grouping users together with respect to their dominant antenna paths. Figures 3 and 4 show the error probability versus the number of users with $E_b/N_0$ =15 dB and for the two urban channels. The preselection scheme employs four antennas. Same observations are made for the three systems.

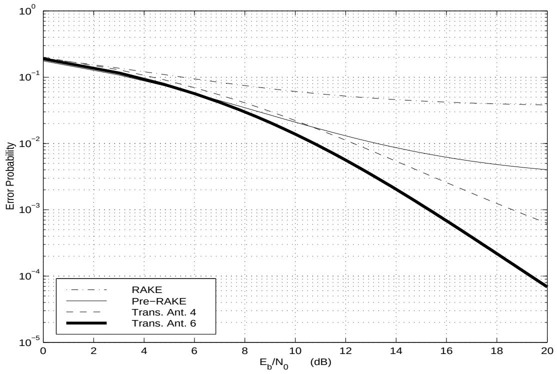

Figure 1. Error probs. in an urban 6-tap channel, K=20

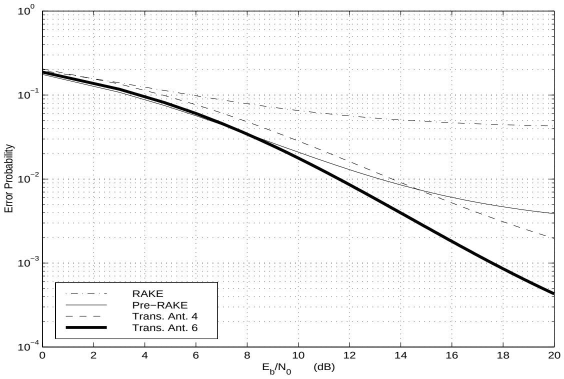

Figure 2. Error probs. in an urban 12 path channel, K=20

## VI. CONCLUSIONS

Three diversity combining techniques for forward link of a DS CDMA system were compared. It was seen that the RAKE receiver's performance is affected by coherent interference due to finite correlations of the code sequences. The pre-RAKE diversity combining scheme provides better performance by avoiding coherent combination of interfering user signals. However, power must be controlled for the pre-RAKE to function well. Otherwise, in the case of weak channel for the user of interest, the performance is poor. The transmit antenna diversity scheme splits users in groups as a function of their strongest path and provides a significant performance gain. It appears, therefore, that power control on the downlink results in appreciable performace gains, especially in the pre-RAKE and the transmit antenna diversity case.

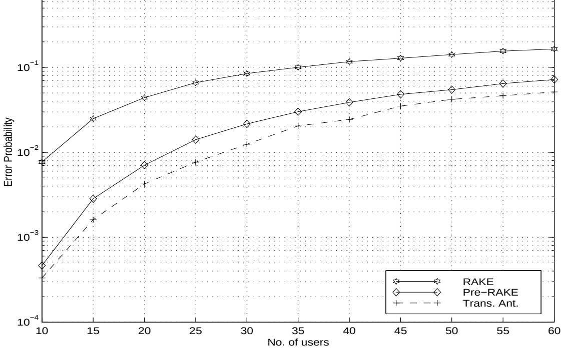

Figure 3. Error prob. vs. no. of users (urban 6 path)

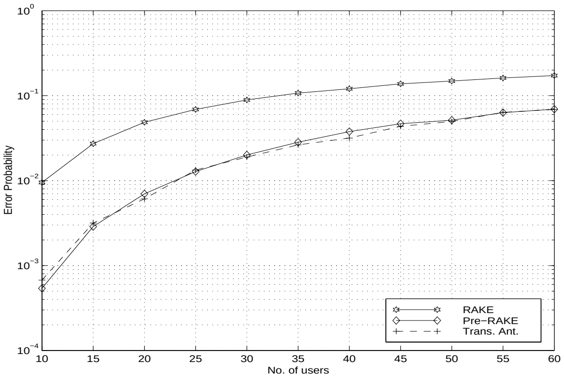

Figure 4. Error prob. vs. no. of users (urban 12 path)

## References

[1] C.-J. Chang and F.-C. Ren. ”Downlink Power Control in DS/CDMA Cellular Mobile Radio Networks”. Intl. Conf. Univer. Pers. Commun., pp. 89–93, Seattle, WA, October 1994.

[2] R. Esmailzadeh, M. Nakagawa, and E. A. Sourour. ”Time-Division Duplex CDMA Communications”. IEEE Pers. Commun. Mag., pp. 51–56, April 1997.

[3] European Telecommunications Standards Institute. European Digital Cellular Telecommunication System: Physical Layer on the Radio Path (GSM 05.02), 1990.

[4] M. Hata. ”Emperical Formulae for Propagation Loss in Land Mobile Radio Services”. IEEE Trans. Veh. Technol., VT-29(3):317–25, 1980.

[5] A. F. Naguib. ”Power Control in Wireless CDMA: Performance Analysis with Cell Site Antenna Array”. Proc. of Globecom, vol. I, pp. 225–229, Singapore, 1995.

[6] J. G. Proakis. Digital Communications. McGraw-Hill, New York, NY, 3rd. edition, 1995.

[7] T. S. Rappaport. Wireless Communications-Principles & Practice. Prentice Hall, Upper Saddle River, NJ, 1996.

[8] A. J. Viterbi. CDMA - Principles of Spread Spectrum Communications. Addison-Wesley, Reading, Mass., 1995.

[9] M. Zorzi. ”Simplified Forward Link Power Control in Cellular CDMA”. IEEE Trans. Veh. Technol., 43(4):1088–1093, November 1994.