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***Abstract*— In this paper, reverse link capacity of a signal-to-interference ratio (SIR) based power-controlled direct-sequence code-division multiple-access (DS-CDMA) system, with the use of an antenna array and a Rake receiver in a multiple cell environment, is investigated. Both transmit and receive beamforming in the reverse link are considered. Instead of using tedious iterative methods, reverse link user capacity represented by a simple closed-form expression is derived, which relates to the number of antennas, the number of Rake receiver fingers, a target SIR, and the processing gain. The most efficient distribution of antenna elements between the base stations and the mobile stations to maximize the user capacity is observed through the numerical results, which also show significant capacity improvement by increasing the number of the antennas and Rake receiver fingers.**

***Index Terms*— CDMA, User capacity, Beamforming, Rake receiver**

I. INTRODUCTION

WITH the advance of wireless communication technology, there is an explosive increase in the number of mobile users. Although second-generation (2G) wireless systems, such as the Global System for Mobile Communications (GSM) and IS-95, are successful in many countries [1], they still cannot meet the requirement of high-speed data and user capacity in high-user-density areas. Code-division multiple access (CDMA) has been chosen as the radio interface technology for 3G systems [2]. Unlike frequency-division multiple access (FDMA) and time-division multiple access (TDMA), which are primarily bandwidth or dimension limited in capacity, CDMA capacity is interference limited [3]. Thus any reduction of the interference will directly lead to capacity increases. The emerging technologies, such as beamforming and multiuser detections, could lead to a significant reduction in the interference and result in many-fold capacity increases [4]. Therefore, capacity estimation is an very important element in the design of CDMA systems and in the evaluation of the new technologies.

Gilhousen et al. [3] estimated CDMA reverse link user capacity of a strength-based power-controlled CDMA system, where total other-cell interference, I, is modelled as Gaussian noise. I increases with the number of active users per cell, N. Kim and Sung estimated the reverse link user capacity of SIR-based power-controlled CDMA systems in [5]. User capacity of multicode CDMA systems supporting voice and data traffic or heterogeneous constant-bit-rate traffic was analyzed in [6]. The effects of a Rake receiver and antenna diversity on reverse link user capacity are further investigated in [7]. Capacity improvement with base-station antenna arrays in strength-based power-controlled cellular CDMA systems has been analyzed [8]. The focus of this paper is to present the user capacity gain of a SIR-based DS-CDMA system in a multicell and multipath fading environment obtained through the use of Rake receiver, transmit and receive beamforming and derive a simple closed-form expression, which is related to the number of the antennas and Rake receiver fingers, a target signal-to-noise-plus-interference ratio (SINR), and the CDMA processing gain, to estimate the reverse link user capacity. In this paper, user capacity is referred to as the number of users that a CDMA system could support at a desired SNIR without power constraints [4]. This paper is organized as follows. System models, including beamforming, Rake receiver, and other-cell interference, are given in Section II. A closed-form equation to evaluate reverse link user capacity of a CDMA cellular system in a multipath fading environment is derived in Section III. Numerical results are given in Section IV. Finally, conclusions are drawn in section V.

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II. SYSTEM MODEL

A. Beamforming

Beamforming has been widely used in wireless systems that employ a fixed set of antenna elements in an array. Considering receive beamforming in reverse link transmissions, the signals from these antenna elements are combined to form a movable beam pattern that can be steered to a desired direction that tracks mobile stations (MS) as they move. This allows the antenna system to focus radio frequency (RF) resources on a particular mobile station and minimize the impact of interference [9], [10]. This is achieved using a beamformer by placing nulls at the directions of interference, while the antenna array gain in the direction of the desired transmitter is maintained constant. Although few antenna elements could be installed at a mobile station, large antenna arrays can be implemented at a base station (BS). When beamforming is used at the mobile station, the transmit beam pattern can be adjusted to minimize the interference to unintended receivers (such as base stations in other cells). At a base station, receive beamforming for each desired user could be implemented independently without affecting the performance of other links [10]. In this paper, the linear equally spaced (LES) array is used for both transmit and receive beamforming in a two-dimensional multi-cell environment (in the horizontal plane) [9]. The distance d between the elements of the LES array is assumed to be 0.5λ, where λ is the carrier wavelength. In the LES array system, a combining network could generate an antenna pattern [9],

$$G(\phi,\theta) = |\frac{\sin(0.5M\pi(\sin\phi - \sin\theta))}{M\sin(0.5\pi(\sin\phi - \sin\theta))}|^2 \quad (1)$$

where M is the number of antenna elements and ϕ is a variable. The beam could be steered to a desired direction θ by varying ϕ. In the remaining of this paper, we will use the antenna pattern specified in (1) to evaluate the impact of beamforming on the CDMA reverse link capacity.

B. Rake Receiver

Multipath propagation in the radio channel leads to deep fading of the received signal. If the paths are independent and resolvable in time domain, i.e., the delay between different paths is greater than the chip duration T_c, a Rake receiver can be used to combine the paths to achieve diversity gains [11]. The multipath fading can be characterized by a power delay profile (PDP), which is uniformly or exponentially distributed [7]. For a uniform PDP, we have

$$\mathrm{E}[a_l] = 1/L, l = 0, 1, \cdots, L-1$$

and for an exponential PDP, we have

$$\mathrm{E}[a_l] = (1 - \exp(-\varepsilon))\exp(-\varepsilon l), l \geq 0$$

where a_l is the square path gain of the lth path, L is the total number of paths in a uniform profile, and ϵ is a decay factor for an exponential profile. Assuming that the Rake receiver at the base station has R fingers, the received power at the output is the combination of the R paths, $X = a_0 + a_1 + \cdots + a_{R-1}$.

C. Other Cell Interference

A cellular structure is shown in Fig. 1 with a reference cell (base station BS_0) and an interference cell (with base station BS_m). In a CDMA cellular system, an MS is power controlled by a BS in its home cell to ensure that the received SNIR at the BS is no less than a target value, assuming that SIR-based power control is in use. Considering a mobile station, $MS_{m,j}$, in the interference cell, let the received power at its base station BS_m be S. The received interference at the base station of the reference cell, BS_0, is [3] $S(r_m/r_0)^\mu 10^{(\xi_0-\xi_m)/10}$, and r_0 and r_m are the distances from $MS_{m,j}$ to BS_0 and BS_m as shown in Fig. 1. μ is a path loss exponent. ξ_0 and ξ_m describe the shadowing processes in the cells of BS_0 and BS_m, and the shadowing processes are assumed to be mutually independent and follow a lognormal distribution with standard deviation σ dB and zero mean. Considering all interfering mobile stations, the total other-cell interference at BS_0 is obtained by integrating the whole cellular coverage area except the reference cell [6],

$$I = \int\int S(r_m/r_0)^\mu 10^{(\xi_0-\xi_m)/10}\phi(\xi_0 - \xi_m, r_m/r_0)\rho dA$$

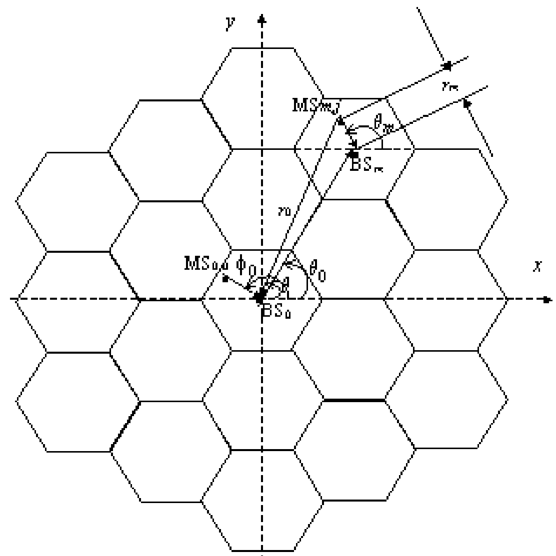

Fig. 1. Cellular structure and reverse link geometry.

where

$$\phi(\xi_0 - \xi_m, r_m/r_0) = \begin{cases} 1, & \text{if}(r_m/r_0)^\mu 10^{(\xi_0-\xi_m)/10} \leq 1 \\ 0, & \text{otherwise} \end{cases}$$

and $\rho = 2N/(3\sqrt{3})$ is the user density per unit area and there are N mobile stations in each cell. This assumes that the users are uniformly distributed in a cell and the radius of the hexagonal cell is normalized to unity. $\phi(\xi_0 - \xi_m, r_m/r_0)$ is an indicator function to show the cell areas that are excluded in the calculation of I since the mobile stations in these areas are not power controlled by BS_m but by BS_0. In computing the above integral, we simply consider the hexagonal areas of each cell rather than the actual coverage area of the base stations [5]-[7].

III. DERIVATION OF REVERSE LINK USER CAPACITY

When beamforming is applied at both transmit and receive sides, the total other-cell interference at BS_0 is expressed as

$$I = \int\int S(r_m/r_0)^\mu 10^{(\xi_0-\xi_m)/10}\phi(\xi_0 - \xi_m, r_m/r_0)\rho \; G_t(\theta,\theta_m)G_r(\theta,\phi_0)dA \quad (2)$$

where

$$\theta = \arctan(\frac{r_1\sin\theta_0 + r_m\sin\theta_m}{r_1\cos\theta_0 + r_m\cos\theta_m})$$

and $G_t(\theta,\theta_m)$ and $G_r(\theta,\phi_0)$ are transmit and receive beamforming gain patterns. θ_m and θ are the azimuth angle of $MS_{m,j}$ to its home base station, BS_m, and that to BS_0, respectively. r_1 is the distance between BS_m to BS_0. θ_0 is the azimuth angle of BS_m to BS_0. ϕ_0 is the azimuth angle of mobile station $MS_{0,0}$ to BS_0 as shown in Fig. 1 and is uniformly distributed from 0 to 2π. When M_t antenna elements are used with the beam pattern shown in (1), the transmit antenna gain in the direction from $MS_{m,j}$ to BS_0 is

$$\begin{aligned} G_t(\theta,\theta_m) &= |\frac{\sin(0.5M_t\pi(\sin(\theta-\pi)-\sin(\theta_m-\pi)))}{M_t\sin(0.5\pi(\sin(\theta-\pi)-\sin(\theta_m-pi)))}|^2 \\ &= |\frac{\sin(0.5M_t\pi(\sin\theta-\sin\theta_m))}{M_t\sin(0.5\pi(\sin\theta-\sin\theta_m))}|^2 \end{aligned} \quad (3)$$

Similarly, when receive beamforming is applied with M_r antenna elements at BS_0 for receiving signals from $MS_{0,0}$, the receive antenna gain in the direction from $MS_{m,j}$ to BS_0 is

$$G_r(\theta,\phi_0) = |\frac{\sin(0.5M_r\pi(\sin\theta-\sin\phi_0))}{M_r\sin(0.5\pi(\sin\theta-\sin\phi_0))}|^2 \quad (4)$$

The mean value of the total other-cell interference I in a multipath fading environment is derived as

$$\mathrm{E}[I] = \mathrm{E}[S]F(\mu,\sigma)N\mathrm{E}[1/X] \quad (5)$$

where

$$\begin{aligned} F(\mu,\sigma) &= \frac{2}{3\sqrt{3}}\exp\{(\sigma\ln(10)/10)^2\}\int\int(\frac{r_m}{r_0})^\mu G_t(\phi,\phi_m) \\ & Q(\frac{10\mu}{\sqrt{2\sigma^2}}\log_{10}(\frac{r_0}{r_m}-\sqrt{2\sigma^2}\frac{\ln(10)}{10}))\mathrm{E}[G_r(\theta,\phi_0)]dA \end{aligned} \quad (6)$$

and

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty \exp(-t^2/2)dt$$

Similarly, the variance of I is given by

$$\mathrm{Var}[I] = \{U(\mu,\sigma)\mathrm{E}[S^2]-V(\mu,\sigma)\mathrm{E}^2[S]\}N\mathrm{E}^2[1/X] \quad (7)$$

where

$$\begin{aligned} U(\mu,\sigma) &= \frac{2}{3\sqrt{3}}\exp\{(\sigma\ln(10)/5)^2\}\int\int(\frac{r_m}{r_0})^{2\mu} G_t^2(\phi,\phi_m) \\ & Q(\frac{10\mu}{\sqrt{2\sigma^2}}\log_{10}(\frac{r_0}{r_m}-\sqrt{2\sigma^2}\frac{\ln(10)}{5}))\mathrm{E}[G_r^2(\theta,\phi_0)]dA \end{aligned} \quad (8)$$

$$\begin{aligned} V(\mu,\sigma) &= \frac{2}{3\sqrt{3}}\exp\{2(\sigma\ln(10)/10)^2\}\int\int(\frac{r_m}{r_0})^{2\mu} G_t^2(\phi,\phi_m) \\ & Q^2(\frac{10\mu}{\sqrt{2\sigma^2}}\log_{10}(\frac{r_0}{r_m}-\sqrt{2\sigma^2}\frac{\ln(10)}{10}))\mathrm{E}^2[G_r(\theta,\phi_0)]dA \end{aligned} \quad (9)$$

The value $F(\mu,\sigma)$, $U(\mu,\sigma)$, and $V(\mu,\sigma)$ can be obtained numerically. For example, when only the first and second-tier cells are considered, we find, for $\mu=4,\sigma=8$ dB, $M_r=3$ and $M_t=1$, $F(4,8)=0.2676$, $U(4,8)=0.1072$ and $V(4,8)=0.0197$.

In the CDMA systems, the received SNIR, E_b/I_0, should be no less than a target value, γ_0, in order to maintain a required transmission quality. Following [6] and [7] and considering the beamforming, we have

$$\begin{aligned} \frac{E_b}{I_0} &\approx \frac{GSG_t(\phi_0,\phi_0)}{\frac{2}{3}(NS\mathrm{E}[G_t(\phi_m,\phi_m)G_r(\phi_m,\phi_0)](1+D)+I)+\eta_0 W} \\ &= \frac{GS}{\frac{2}{3}(\mathrm{E}[G_r(\phi_m,\phi_0)]SN(1+D)+I)+\eta_0 W} \geq \gamma_0 \end{aligned} \quad (10)$$

where

$$D = \begin{cases} \mathrm{E}[1/X](L-R)/R, & \text{for uniform PDP} \\ \mathrm{E}[1/X]\exp(-\epsilon R), & \text{for exponential PDP} \end{cases}$$

and G is the CDMA processing gain, η_0 is the single-sided white noise power spectrum density and W is the spreading bandwidth. The factor 2/3 in the denominator is due to the assumption of a square chip pulse. The denominator in (10) includes other-cell interference as well as own-cell interference due to other mobile stations in the reference cell. Note that the transmit antenna gains of mobile stations at the reference cell in (10) are all set to unity since their transmit beams are steered toward base station BS_0. ϕ_m is the azimuth angle of an interfering mobile station $MS_{0,m}$ to BS_0. $G_r(\phi_m,\phi_0)$ is the receive beamforming gain of $MS_{0,0}$ to direction of $MS_{0,m}$. ϕ_m and ϕ_0 are uniformly distributed in $[0,2\pi)$. Let $\phi=\sin\phi_m-\sin\phi_0$, the probability density function of ϕ is found to be

$$f(\phi) = \begin{cases} \frac{1}{\pi^2}\int_{-1}^{\phi+1}\frac{1}{\sqrt{(1-\tau^2)(1-(\phi-\tau)^2)}}d\tau, & -2<\phi<0 \\ \frac{1}{\pi^2}\int_{\phi-1}^{1}\frac{1}{\sqrt{(1-\tau^2)(1-(\phi-\tau)^2)}}d\tau, & 0\leq\phi<2 \\ 0, & \text{otherwise} \end{cases} \quad (11)$$

We further have

$$\mathrm{G_r} = \mathrm{E}[G_r(\phi_m,\phi_0)] = \int_{-2}^{2}\frac{\sin^2(0.5M_r\pi\phi)}{M_r^2\sin^2(0.5\pi\phi)}f(\phi)d\phi$$

Let S be the minimum power level satisfying (10). The received power S could be expressed in terms of I as

$$S = \frac{I+1.5\eta_0 W}{C} \quad (12)$$

where

$$C = 1.5G/\gamma_0 - \mathrm{G_r}N(1+D)$$

Now the user capacity N can be found via an iterative method [6], [7], in which, there are two concatenated iteration loops. In the inner loop, for a given N value, determine $\mathrm{E}[I]$ and $\mathrm{Var}[I]$ using the following steps: *1*. Set $\mathrm{E}[I]$ and $\mathrm{Var}[I]$ as zeros. *2*. Calculate $\mathrm{E}[I]$ and $\mathrm{Var}[I]$ from (12). *3*. Calculate $\mathrm{E}[I]$ and $\mathrm{Var}[I]$ from (5) and (7). *4*. Repeat steps 2 and 3 until the differences between old and new values of $\mathrm{E}[I]$ and $\mathrm{Var}[I]$ are less than 1% [7]. Using the $\mathrm{E}[I]$ and $\mathrm{Var}[I]$ obtained above and a specified maximum transmission power limit, calculate an outage probability (the transmission power exceeds the power constraint) [7]. If the outage probability does not exceed a required level, the outer loop increases N by 1 and enters the inter loop. Otherwise the iteration loops stop and we obtain the user capacity as $N-1$. The iterative method to determine user capacity as described above is computationally complicated due to multiple loops of numerical integrations. In this paper, we derive a formula to directly estimate user capacity, which is related to all the relevant factors, such as γ_0, beamforming gains and CDMA processing gains. Solving equations (5), (7) and (12), we get

$$\mathrm{E}[I] = \frac{1.5NF(\mu,\sigma)\mathrm{E}[1/X]}{C-NF(\mu,\sigma)\mathrm{E}[1/X]}\eta_0 W \quad (13)$$

(M_t, M_r)	$(1,1)$	$(1,3)$	$(1,5)$	$(1,7)$	$(1,9)$
$F(\mu,\sigma)$	0.6611	0.2676	0.1724	0.1287	0.1035
$U(\mu,\sigma)$	0.2252	0.1072	0.0691	0.0516	0.0414
$V(\mu,\sigma)$	0.0451	0.0197	0.0127	0.0094	0.0075
$\mathrm{G_r}$	1	0.3855	0.2487	0.1863	0.1501

TABLE I

COMPUTATIONAL PARAMETERS WITH $M_t = 1$

(M_t, M_r)	$(2,1)$	$(2,3)$	$(2,5)$	$(2,7)$	$(2,9)$
$F(\mu,\sigma)$	0.3410	0.1458	0.0960	0.0726	0.0589
$U(\mu,\sigma)$	0.1329	0.0570	0.0379	0.0288	0.0234
$V(\mu,\sigma)$	0.0225	0.0100	0.0067	0.0051	0.0041

TABLE II

COMPUTATIONAL PARAMETERS WITH $M_t = 2$

$$\mathrm{Var}[I] = \frac{(U(\mu,\sigma) - V(\mu,\sigma))\mathrm{E}^2[1/X]}{C^2/N - U(\mu,\sigma)\mathrm{E}^2[1/X]}(\mathrm{E}[I] + 1.5\eta_0 W)^2 \tag{14}$$

It is obvious that $\mathrm{E}[I]$ and $\mathrm{Var}[I]$ are greater than 0 because the noise or interference power is always positive. Thus a valid N has to ensure (13) and (14) greater than 0. Due to the conditions $\mathrm{E}[I] \geq 0$ and $\mathrm{Var}[I] \geq 0$, we are able to determine user capacity N as

$$N = \lfloor \frac{1.5G/\gamma_0}{\mathrm{G_r}(1 + D) + \mathrm{E}[1/X]F(\mu,\sigma)} \rfloor \tag{15}$$

where $\lfloor x \rfloor$ indicates the maximum integer no greater than x. In using the iterative method to determine the user capacity, we found that, when the number of users is above the user capacity, power control will not work, since every mobile station tries to satisfy the target SNIR, γ_0, by increasing its transmit power until reaching its maximum transmit power allowed. This leads to an increase of interference to other users. The results from the closed-form expression, (15), will be compared in Section IV with those results obtained from the iterative method.

IV. NUMERIC RESULTS

Through this section we assume propagation parameters, $\mu = 4$ and $\sigma = 8$ dB. The basic data rate R, is assumed to be 32 Kbps and the spreading chip rate is 4.096 Mbps. The traffic type is of the basic rate and its required SNIR target γ_0 is 5 dB. Table 1 considers a single transmit antenna element, and at the receive side, the number of antenna elements varies from 1, 3, 5, 7, to 9. As $F(\mu,\sigma)$ is proportional to other-cell interference, we see that the value of $F(\mu,\sigma)$ decreases with an increase number of receive antenna elements, M_r. The received own-cell interference is proportional to the expected received antenna gain, G_r, which decreases with increasing M_r as shown in the table. The values of $U(\mu,\sigma)$ and $V(\mu,\sigma)$, are also presented in the table, which will be used in evaluating user capacity via the iterative method as described in Section III. Table 2 is similar to Table 1 except that the different number of transmit antenna elements is considered.

Fig. 2 presents the reverse link user capacity without considering the multipath fading environment, which is similar to

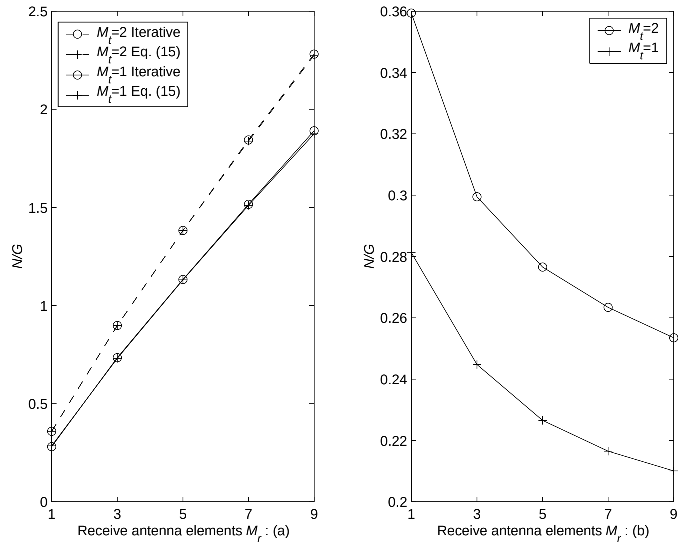

Fig. 2. User capacity, (a) Effect of beamforming, (b) Per receive antenna element.

the situation $R = L$ (L is large enough) in a uniform PDP fading environment, and illustrates the effect of the number of receive antenna elements. Fig. 2 (a) clearly shows that the user capacity increases significantly when the number of antenna elements increases. However, as shown in Fig. 2 (b), the user capacity per antenna drops with the increase of antenna elements. In Fig. 2 (a), we also compare the capacity evaluations using a simple closed-form expression, (15), and those based on the complex iterative method, where the outage probability as discussed in Section III is assumed to be 0.05 [7]. Almost identical capacity results are obtained using the two evaluation methods. Based on numerical calculations, for some cases, they give identical results. In some other scenarios, they only differ by one user in capacity evaluations. For example, when $M_r = 5$ and $M_t = 1$, from (11), we obtain $N = 144$. When the iterative method is used, we get $N = 145$, which corresponds to an outage probability of 0.015. However, a close examination reveals that the system with 145 users is not sustainable (not practical) since the mean other-cell interference reaches $\mathrm{E}[I] \approx 1244\eta_0 W$. Note that, when N =144, we have $\mathrm{E}[I] \approx 114\eta_0 W$. Recall that, in Section III, a simple closed-form expression is derived to evaluate user capacity. Fig. 2 (a) illustrates the effectiveness and accuracy of this approach in evaluating user capacity. Fig. 3 presents the capacity results when $M_t + M_r$ = 4, 6, 8, and 10. When $M_t + M_r$ = 4, it is seen that maximum capacity is achieved when $M_t = 1 (M_r = 3)$. For cases with $M_t + M_r$ = 6, 8, and 10, maximum capacity is achieved when $M_t = 2$. The numerical results indicate that, to obtain higher reverse-link user capacity, it is desirable to put more antenna elements at the receive sides (base station) compared to the transmit side (mobile station). The numerical results also suggest that, when $M_t + M_r$ is small, say 4, only one antenna element should be placed at the transmit side. When $M_t + M_r$ increases to 6, 8, or 10, two antenna elements should be used at the transmit side. With further increasing $M_t + M_r$, it is expected that the

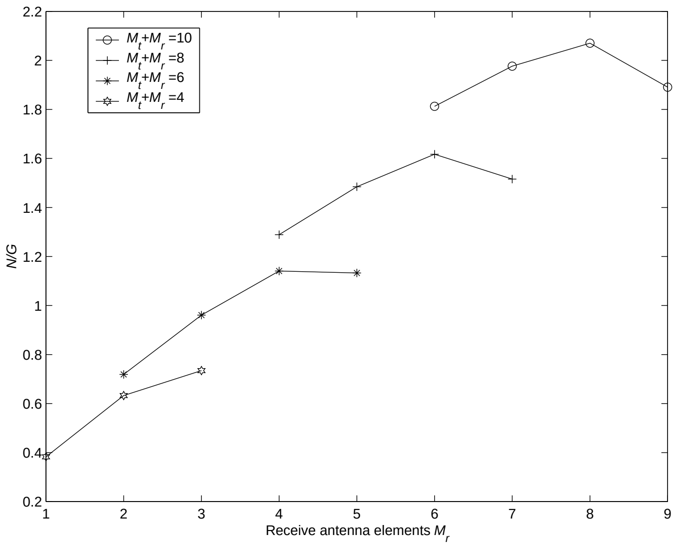

Fig. 3. User capacity, impact of antenna element distribution between transmitter and receiver.

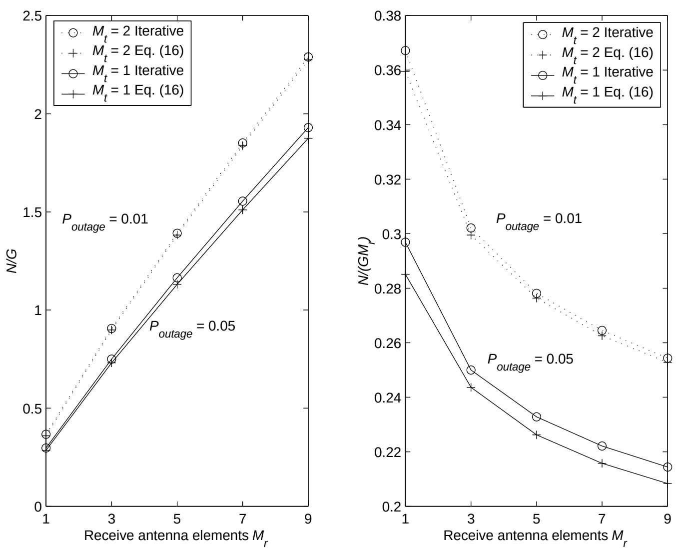

Fig. 4. User capacity, effect of beamforming and Rake receiver for the exponential PDP fading environment.

number of antenna elements at the transmit side should be increased.

Assuming a mutlipath environment with $L = 4$, the numerical results of user capacity for the exponential power delay profile are presented in Fig. 4. For comparison purpose, the number of transmit antenna elements, M_t, is set to be of 1 and 2, and the number of Rake receiver fingers, R, varies from 2, 3 to 4. Noticeable capacity improvements are seen when the number of Rake receiver fingers increases, which indicates the effectiveness of the Rake receiver in combination with the use of beamforming.

V. CONCLUSIONS

A simple closed-form expression is derived to evaluate reverse link user capacity for the DS-CDMA systems with the antenna arrays and Rake receivers in a multicell environment. Both transmit and receive beamforming are assumed in the system and significant capacity improvements are observed with an increase of the number of antenna elements and Rake receiver fingers. The relationships between the capacity and various system parameters, including the target SNIR, CDMA processing gain, antenna array gain patterns, and the number of Rake receiver fingers, are reflected in the simple closed-form capacity equation.

In this paper we consider an LES array for beamforming and perfect fast transmit power control in the system. In a practical system, the loop delay of power control and the accuracy of SNIR estimation will have an impact on the performance of power control, which reduces the CDMA capacity. Furthermore, in a multipath environment, signals arrive at the receiver through multiple paths from different directions, which will increase the complexity to steer the beam to each direction. All these practical issues affecting the real system capacity will be studied.

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