Transactions Letters

Capacity Analysis in CDMA Distributed Antenna Systems

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***Abstract*—In this letter, the effect of maximal ratio combining (MRC)-based macrodiversity on the reverse-link and forward-link capacity in code division multiple access (CDMA)-distributed antenna systems is analyzed. The concept of virtual cell is illustrated, and the analytical outage probability expressions are derived. The present investigation shows that on the reverse link, the interference can be suppressed greatly with macrodiversity, which leads to a significant increase in capacity. However, on the forward-link, it is proven that if simulcasting is used in CDMA-distributed antenna systems, the forward-link capacity cannot increase with macrodiversity whatever power allocation scheme is adopted. Based on the analysis of the cause of capacity loss, a new transmission scheme is further presented and the optimal power allocation scheme is derived. It is shown that, in this case, the forward-link capacity increases rapidly with the number of involved distributed antennas.**

***Index Terms*—CDMA, distributed antenna, forward-link capacity, macrodiversity, maximal ratio combining (MRC), reverse-link capacity.**

I. Introduction

INTEREST in microcellular has grown rapidly over the last decade. Microcellular architecture emphasizes the use of low power radio technology to achieve high capacity through massive frequency reuse and has been applied widely in present personal communications service (PCS) systems. However, in microcellular systems, a large number of expensive base stations (BSs) and frequent handoffs between microcells are needed, which leads to high cost and unstable performance. In order to solve these problems, distributed antenna system (DAS) was proposed, in which many remote antenna ports are distributed over a large area and connected to a single BS by fiber, fiber/coax cable, or microwave link [1]–[4].

In DAS, remote antenna ports are only used to receive signals (i.e., down-conversion, electric-to-optical conversion, etc.) on the reverse link and transmit signals on the forward link. No sophisticated signal processing techniques are carried out at those antennas so that their size and cost decrease and can be installed like street lamps every few hundred meters. At the central BS, the signals associated with different connected remote antennas are processed using all kinds of advanced signal processing techniques. With remote antennas, each mobile can communicate with multiple antennas simultaneously wherever it is in the system. Therefore, compared to the conventional cellular systems, DAS can achieve higher capacity[1] and a global coverage with lower operation and maintenance costs.

Code division multiple access (CDMA) has been applied to DAS thanks to its superior interference suppressing capability [5]–[10]. The reverse-link power control was investigated in [7], and the simulation results showed that the distributed architecture can bring significant power savings. The forward-link performance of a simulcasting DAS in noise-limited and interference-limited conditions was evaluated in [8]. Besides, measurement results for the in-building CDMA DAS and numerical results for applying distributed antennas to GSM and joint detection (JD)-CDMA can be found in [9] and [10], respectively.

Nevertheless, most of the previous work focus on the performance simulations. In this letter, we build a detailed analytical CDMA DAS model and derive the outage probability expressions on the reverse link and the forward link. It is assumed that all the desired signals received by the involved remote antennas are combined by maximal ratio combining (MRC), and these antennas simulcast the same signals to the desired mobile. It will be shown that the reverse-link capacity increases greatly with the number of involved remote antennas while the forward-link capacity does not. We prove that whatever power allocation scheme is adopted, macrodiversity cannot improve the forward-link capacity if simulcasting is used in CDMA DAS. Selective transmission achieves the maximum forward-link capacity. We further present a new transmission scheme with which some joint control among the involved antennas is made to assure that the signals arrived at the desired mobile in phase and simultaneously. It is proven that in this case, a power allocation scheme can be found in which the received signal-to-interference ratio (SIR) is improved as the number of involved antennas increases. Nevertheless, the capacity enhancement is gained at the cost of high complexity.

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[1] In this letter, the term "capacity" refers to the number of users that can be supported at the desired quality-of-service requirement. This should be distinguished from the information-theoretic capacity of a channel.

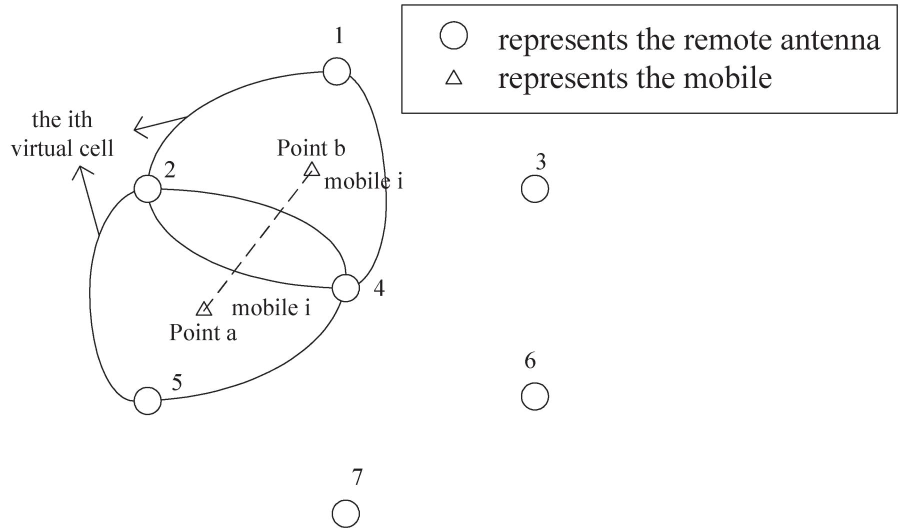


Fig. 1. Virtual cell in CDMA DAS.

The remainder of this letter is organized as follows. In Section II, we provide the system model and present the key assumptions. The outage probability expressions on the reverse link and the forward link are derived in Sections III and IV, respectively. Numerical results are presented in Section V. Finally, Section VI summarizes and concludes this letter.

II. System Model

Consider a CDMA DAS with L remote antennas that are placed evenly and symmetrically. Here, the present cellular structure is removed, and the cells are divided not geographically, but according to the user demands. We call the cell "virtual cell." In particular, the remote antennas serving for mobile i form the $i\text{th}$ virtual cell. When mobile i moves, the remote antennas in the $i\text{th}$ virtual cell will be dynamically modified to adapt to the changes of mobile i. As shown in Fig. 1, antennas 2, 4, and 5 make up the $i\text{th}$ virtual cell when mobile i is located at point a, while at point b, its virtual cell consists of antennas 1, 2, and 4. The BS continuously measures the channel gain between mobile i and each remote antenna and selects the best H remote antennas to form the virtual cell of mobile i.[2]

Assume that, in total, K mobiles are uniformly distributed in the system with only one antenna at each mobile. The transmitted signal is a pseudo noise (PN)-code-modulated bit stream with a spreading factor (processing gain) of N. Assume that the voice activity variable has a Bernoulli distribution with probability of success λ and the effect of thermal noise is ignored in the interference-limited environment. Assume that the channel gain can be known at the BS and the mobile receiver through measurement so that MRC can be adopted both at the BS and every mobile. The channel is assumed to be frequency nonselective and the fading variable is a complex random variable that combines both the fast fading and log-normal shadowing effects, namely, its module has a Rayleigh distribution and its mean square value is a log-normal random variable with mean zero and variance σ_s^2. The advantage of multiuser detector is not investigated in this letter, and, thus, we assume that the conventional matched filter is used at the BS and mobiles. Throughout the letter, we denote by $(\cdot)^{\mathrm{T}}$ and $(\cdot)^*$ the transpose and the conjugate and transpose operators, respectively.

III. Capacity Analysis on the Reverse Link

The received signal vector of the antennas in the virtual cell of mobile 0[3] is

$$\mathbf{X(t)} = \sum_{i=0}^{K-1} \psi_i \sqrt{P_i}\mathbf{S_i(t)}\boldsymbol{\gamma_i} + \mathbf{n(t)} \tag{1}$$

where ψ_i and P_i are the voice activity variable and the transmission power of mobile i, respectively. $\boldsymbol{\gamma}_i = (\gamma_{i,0}, \ldots, \gamma_{i,H-1})^{\mathrm{T}}$ is an $H \times 1$ vector that represents the channel gain between mobile i and each antenna in virtual cell (VC) 0, where $\gamma_{i,j} = (r_{i,j}^{-\alpha})^{1/2} \cdot \beta_{i,j}$, $r_{i,j}$ is the distance from mobile i to antenna j and $\beta_{i,j}$ is the amplitude fading variable along the path between mobile i and antenna j , $j = 0, \ldots, H-1$. $\mathbf{S_i(t)}$ is an $H \times H$ diagonal matrix with the diagonal element $s_{j,j}(t) = b_i(\lfloor(t - \tau_{i,j})/T\rfloor)c_i(t-\tau_{i,j})$, where $b_i(\cdot)$ denotes the transmitted bit of mobile i in duration T, $c_i(\cdot)$ is the spreading code used by mobile i, and $\tau_{i,j}$, is the propagation delay from mobile i to antenna j, $j = 0, \ldots, H-1$. $\mathbf{n(t)}$ is the thermal noise vector.

The $j\text{th}$ element of the output $H \times 1$ vector of the matched filters can then be written as

$$Y_j(l) = \int_{t_{1j}}^{t_{2j}} c_0(t-\tau_{0,j})X_j(t)dt = E_j(l) + \sum_{i=1}^{K-1} \psi_i I_{ij}(l) + n_j(l) \tag{2}$$

[2]Here, the channel gain is referred to the reverse-link channel gain measured by the BS. In time division duplexing (TDD) mode, the difference between the reverse-link channel gain and the forward-link channel gain is so slight that it can be ignored. Therefore, here, we assume that the best H remote antennas are selected based on the measurement of the reverse-link channel gain.

[3]The virtual cell of mobile 0 is called "VC 0" for short in the following text.

where

$$E_j(l)=\int_{t_{1j}}^{t_{2j}} \sqrt{P_0}b_0\left(\left\lfloor\frac{(t-\tau_{0,j})}{T}\right\rfloor\right)c_0(t-t\tau_{0,j})c_0(t-\tau_{0,j})\gamma_{0,j}\,dt$$

$$I_{ij}(l)=\int_{t_{1j}}^{t_{2j}} \sqrt{P_i}b_i\left(\left\lfloor\frac{(t-\tau_{i,j})}{T}\right\rfloor\right)c_i(t-\tau_{i,j})c_0(t-\tau_{0,j})\gamma_{i,j}\,dt$$

$$t_{1j}=(l-1)T-\tau_{0,j}, \text{ and } t_{2j}=lT-\tau_{0,j}$$
$$\text{for } j=0,\ldots,H-1.$$

All the output branches are combined with MRC, and, thus, we have

$$\begin{aligned} z(l) &= \boldsymbol{\gamma_0^*}\mathbf{Y(l)} \\ &= N\sqrt{P_0}b_0(l)\boldsymbol{\gamma_0^*\gamma_0} + \sum_{i=1}^{K-1}\psi_i\boldsymbol{\gamma_0^*}\mathbf{I_i(l)} + \boldsymbol{\gamma_0^*}\mathbf{n(l)} \\ &= z_0(l)+z_1(l)+z_2(l). \end{aligned} \tag{3}$$

It can be further derived that $\mathrm{Var}(z_0(l)) = N^2P_0\|\gamma_0^*\gamma_0\|^2$ and $\mathrm{Var}(z_1(l)) = N\sum_{i=1}^{K-1}\psi_iP_i\|\gamma_0^*\boldsymbol{\gamma_i}\|^2$.

Assume a perfect instantaneous power control, i.e., after being combined the desired signal power received by each mobile's virtual cell is equal to P'. Then, by ignoring the thermal noise and applying this power control scheme, the bit energy to interference and noise density ratio can be written as

$$\begin{aligned} \frac{E_b}{N_0+I_0} &\approx \frac{E_b}{I_0} \\ &= \frac{N^2P_0\left\|\boldsymbol{\gamma_0^*\gamma_0}\right\|^2}{N\sum\limits_{i=1}^{K-1}\psi_iP_i\left\|\boldsymbol{\gamma_0^*\gamma_i}\right\|^2} \\ &= \frac{N}{\sum\limits_{i=1}^{K-1}\psi_i\frac{\left\|\boldsymbol{\gamma_0^*\gamma_i}\right\|^2}{\|\boldsymbol{\gamma_0}\|^2\left\|\boldsymbol{\gamma_{i_x}}\right\|^2}} \end{aligned} \tag{4}$$

where $\boldsymbol{\gamma_{i_x}}$ represents the channel gain between mobile i and each antenna in its own virtual cell.

Let δ be the E_b/I_0 value required to achieve the level of performance. The outage probability is then given by

$$P_{\text{out}} = P_r\left(\frac{E_b}{I_0}<\delta\right) = P_r\left(I>\frac{N}{\delta}\right) \tag{5}$$

where $I=\sum_{i=1}^{K-1}\psi_i\xi_i$ and $\xi_i=\|\gamma_0^*\boldsymbol{\gamma_i}\|^2/\|\gamma_0\|^2\|\boldsymbol{\gamma_{i_x}}\|^2$. For a large number of mobiles, I (interference due to $K-1$ users) can be approximated by a Gaussian random variable with the mean $\mu_I=(K-1)\cdot E(\psi_i\xi_i)=(K-1)\cdot\lambda\mu_\xi$ and variance $\sigma_I^2=(K-1)\cdot \mathrm{Var}(\psi_i\xi_i) = (k-1)\cdot[\lambda(\mu_\xi^2+\sigma_\xi^2)-\lambda^2\mu_\xi^2]$, where μ_ξ is the mean of ξ_i and σ_ξ^2 is the variance of ξ_i.

Finally, we have

$$P_{\text{out}} = Q\left(\frac{\frac{N}{\delta}-\mu_l}{\sigma_l}\right) \tag{6}$$

where $Q(x)=(1/\sqrt{2\pi})\int_x^\infty \mathrm{e}^{-y^2/2}dy$. This equation gives the outage probability as a function of the number of mobiles that can be supported. The numerical results are presented in Section V.

IV. Capacity Analysis on the Forward Link

Now, consider the forward-link capacity. Assume that coherent demodulation can be achieved by sending a pilot with other traffic channels. The power of the pilot channel is assumed to be P, which is equal to the total allocated power of each mobile. Since each signal from the involved remote antennas to the mobile propagates through a distinct path and arrives at the mobile with independent fading, some power allocation scheme among the involved antennas should be adopted. Assume that the power allocated to mobile k from antenna $l_{k,i}$ is $\varpi_{k,l_{k,i}}^2\cdot P$, where $l_{k,i}$ is the number of the ith antenna in VC k and $\varpi_{k,l_{k,i}}$ represents the weight. Obviously, we have $\forall k$, $\sum_{i=0}^{H-1}\varpi_{k,l_{k,i}}^2=1$. For every mobile in the system, we can adjust its weight vector to achieve the best performance.

Assume that the antennas in VC 0 are numbered from 0 to $H-1$. Then, the received signal of mobile 0 is

$$\begin{aligned} x(t) =& \sum_{i=0}^{L-1}\sum_{m_i=0}^{K_i-1}\psi_{m_i}\sqrt{P}\varpi_{m_i,i}\gamma_{0,i}b_{m_i}\left(\left\lfloor\frac{t-\tau_{0,i}}{T}\right\rfloor\right)c_{m_i}(t-\tau_{0,i}) \\ &+\sum_{i=0}^{L-1}\sqrt{P}\gamma_{0,i}b_i'\left(\left\lfloor\frac{t-\tau_{0,i}}{T}\right\rfloor\right)c_i'(t-\tau_{0,i})+n(t) \end{aligned} \tag{7}$$

where K_i is the number of mobiles that communicate with antenna i. $\gamma_{0,i}$ represents the channel gain between mobile 0 and antenna i. $b_i'(\cdot)$ represents the pilot bit of antenna i in duration T and $c_i'(\cdot)$ is the spreading code used by the pilot of antenna i.

By regarding the signals from different antennas in VC 0 to mobile 0 as multiple paths of the desired signal, we can separate the paths with a RAKE receiver, and the jth branch is

$$\begin{aligned} y_j(l) =& N\sqrt{P}b_0(l)\varpi_{0,j}\gamma_{0,j}+\sqrt{P}\sum_{\substack{i=0\\i\neq j}}^{H-1}\varpi_{0,i}\gamma_{0,i}I_{i,j}(l) \\ &+\sqrt{P}\sum_{i=0}^{H-1}\sum_{m_i=1}^{K_i-1}\psi_{m_i}\varpi_{m_i,i}\gamma_{0,i}I_{m_i,j}(l) \\ &+\sqrt{P}\sum_{i=H}^{L-1}\sum_{m_i=0}^{K_i-1}\psi_{m_i}\varpi_{m_i,i}\gamma_{0,i}I_{m_i,j}(l) \\ &+\sqrt{P}\sum_{i=0}^{L-1}\gamma_{0,i}I_{i,j}'(l)+n_T(l) \\ =& z_0(l)+z_1(l)+z_2(l)+z_3(l)+z_4(l)+n_T(l) \end{aligned} \tag{8}$$

where

$$I_{i,j}(l) = \int_{t_{ij}}^{t_{2j}} b_0\left(\left\lfloor \frac{(t-\tau_{0,i})}{T} \right\rfloor\right) c_0(t-\tau_{0,i}) c_0(t-\tau_{0,j}) dt$$

$$I_{m_i,j}(l) = \int_{t_{1j}}^{t_{2j}} b_{m_i}\left(\left\lfloor \frac{(t-\tau_{0,i})}{T} \right\rfloor\right) c_{m_i}(t-\tau_{0,i}) c_0(t-\tau_{0,j}) dt$$

$$I'_{i,j}(l) = \int_{t_{1j}}^{t_{2j}} b'_i\left(\left\lfloor \frac{(t-\tau_{0,i})}{T} \right\rfloor\right) c'_i(t-\tau_{0,j}) c_0(t-\tau_{0,j}) dt$$

$$t_{1j} = (l-1)T - \tau_{0,j}, \text{ and } t_{2j} = lT - \tau_{0,j}.$$

Similarly, it can be further derived that

$$\mathrm{Var}\,(z_0(l)) = N^2 P(\varpi_{0,j}\gamma_{0,j})^2$$

$$\mathrm{Var}\,(z_1(l)) = NP \sum_{\substack{i=0 \\ i\neq j}}^{H-1} (\varpi_{0,i}\gamma_{0,i})^2$$

$$\mathrm{Var}\,(z_2(l)) = NP \sum_{i=0}^{H-1} \gamma_{0,i}^2 \sum_{m_i=1}^{K_i-1} (\psi_{m_i}\varpi_{m_i,i})^2$$

$$\mathrm{Var}\,(z_3(l)) = NP \sum_{i=H}^{L-1} \gamma_{0,i}^2 \sum_{m_i=0}^{K_i-1} (\psi_{m_i}\varpi_{m_i,i})^2$$

$$\text{and } \mathrm{Var}\,(z_4(l)) = NP \sum_{i=0}^{L-1} \gamma_{0,i}^2.$$

For a large number of mobiles, the random variable K_i can be approximated by a Poisson random variable with the mean KH/L. It is proven in Appendix that

$$\lim_{K\to\infty} \frac{\sqrt{\mathrm{Var}\left[\sum_{m_i=0}^{K_i-1} (\psi_{m_i}\varpi_{m_i,i})^2\right]}}{E\left[\sum_{m_i=0}^{K_i-1} (\psi_{m_i}\varpi_{m_i,i})^2\right]} = 0. \tag{9}$$

Equation (9) demonstrates that for a large number of mobiles, the fluctuation around the mean of the interference generated by each involved antenna can be neglected. Therefore, $\sum_{m_i=0}^{K_i-1}(\psi_{m_i}\varpi_{m_i,i})^2$ can be replaced by the mean $E[\sum_{m_i=0}^{K_i-1}(\psi_{m_i}\varpi_{m_i,i})^2] = \lambda K/L$ approximately. Using MRC, we have (10). In (10), shown at the bottom of the page, it can be seen that E_b/I_0 depends on specific power allocation scheme, i.e., the weight vector $\mathbf{w_0} = (\varpi_{0,0}, \ldots, \varpi_{0,H-1})$ of mobile 0. Assume that $g(\mathbf{w_0}) = \sum_{i=0}^{H-1}(\varpi_{0,i}\gamma_{0,i})^2$. It can be proven that when $\mathbf{w_0} = \mathbf{w_0^*} = (0, \ldots, 0, 1, 0, \ldots, 0)$, $g(\mathbf{w_0^*}) = \max_{\mathbf{w_0}} g(\mathbf{w_0}) = \gamma_{0,x}^2$, where $\varpi_{0,x} = 1$ and $\gamma_{0,x} = \max\{\gamma_{0,0}, \ldots, \gamma_{0,H-1}\}$. According to (10), such a scheme is the best one with which E_b/I_0 of mobile 0 is maximized, and, thus, the maximum forward-link capacity can be achieved. Obviously, this is the well-known selective transmission scheme.

By far, we have proven that in various power allocation schemes, the scheme focusing all the transmission power on the antenna that offers the least attenuation is the best. As illustrated in [12], with the traditional transmission scheme, the received signal power at the mobile is the sum of the power received from each involved antenna. Therefore, by assuming that the total power allocated to each mobile is a constant, which means that the total interference is fixed, it is clear that distributing the transmission signal power among several antennas will cause a decrease of the received SIR compared with the case without

$$\begin{aligned}
\frac{E_b}{I_0} &= \sum_{j=0}^{H-1} \left(\frac{E_b}{I_0}\right)_j \\
&= \sum_{j=0}^{H-1} \frac{N \cdot (\varpi_{0,j}\gamma_{0,j})^2}{\sum\limits_{\substack{i=0\\ i\neq j}}^{H-1} (\varpi_{0,i}\gamma_{0,i})^2 + \left(\frac{\lambda K}{L} - \frac{\lambda}{H}\right) \sum\limits_{i=0}^{H-1} \gamma_{0,i}^2 + \left(\frac{\lambda K}{L}\right) \sum\limits_{i=H}^{L-1} \gamma_{0,i}^2 + \sum\limits_{i=0}^{L-1} \gamma_{0,i}^2} \\
&\approx \frac{N \cdot \sum\limits_{j=0}^{H-1} (\varpi_{0,j}\gamma_{0,j})^2}{\left(\frac{\lambda K}{L+1}\right) \sum\limits_{i=0}^{L-1} \gamma_{0,i}^2}
\end{aligned} \tag{10}$$

macrodiversity. Nevertheless, if the phases and timing of the transmitted signals are adjusted to assure that the desired signals arrive at the mobile receiver in phase and simultaneously, the total received signal power is not the sum of the power of each signal, but the square of the sum of the amplitude of each signal. When the number of involved antennas increases, the signal power increases in proportion to its square, while the interference power increases with it linearly. Thus, the received SIR may be improved in this new transmission scheme, and even forward-link capacity benefits may be brought.

In particular, assume that the desired signals from the antennas in VC 0 are jointly adjusted in order to arrive at mobile 0 in phase and simultaneously. Then, the output of the matched filter is given by

$$\begin{aligned} y(l) &= N\sqrt{P} b_0(l) \sum_{i=0}^{H-1} \varpi_{0,i}\gamma_{0,i} \\ &\quad + \sqrt{P}\sum_{i=0}^{H-1}\sum_{m_i=1}^{K_i-1} \psi_{m_i}\varpi_{m_i,i}\gamma_{0,i} I_{m_i}(l) \\ &\quad + \sqrt{P}\sum_{i=H}^{L-1}\sum_{m_i=0}^{K_i-1} \psi_{m_i}\varpi_{m_i,i}\gamma_{0,i} I_{m_i}(l) \\ &\quad + \sqrt{P}\sum_{i=0}^{L-1}\gamma_{0,i} I'_i(l) + n_T(l) \\ &= z_0(l)+z_1(l)+z_2(l)+z_3(l)+n_T(l) \end{aligned} \tag{11}$$

where

$$\begin{aligned} I_{m_i}(l) &= \int_{t_1}^{t_2} b_{m_i}\left(\left\lfloor \frac{(t-\tau_{0,i})}{T}\right\rfloor\right) c_{m_i}(t-\tau_{0,i}) c_0(t-\tau_{0,0})\,dt \\ I'_i(l) &= \int_{t_1}^{t_2} b'_i\left(\left\lfloor \frac{(t-\tau_{0,i})}{T}\right\rfloor\right) c'_i(t-\tau_{0,i}) c_0(t-\tau_{0,0})\,dt \\ t_1 &= (l-1)T-\tau_{0,0}, \quad t_2 = lT-\tau_{0,0} \end{aligned}$$

and it can be derived that

$$\begin{aligned} \mathrm{Var}\,(z_0(l)) &= N^2 P\left(\sum_{i=0}^{H-1}\varpi_{0,i}\gamma_{0,i}\right)^2 \\ \mathrm{Var}\,(z_1(l)) &= NP\sum_{i=0}^{H-1}\gamma_{0,i}^2 \sum_{m_i=1}^{K_i-1}(\psi_{m_i}\varpi_{m_i,i})^2 \\ \mathrm{Var}\,(z_2(l)) &= NP\times\sum_{i=H}^{L-1}\gamma_{0,i}^2 \sum_{m_i=0}^{K_i-1}(\psi_{m_i}\varpi_{m_i,i})^2 \\ \text{and } \mathrm{Var}\,(z_3(l)) &= NP\times\sum_{i=0}^{L-1}\gamma_{0,i}^2. \end{aligned}$$

The bit energy-to-interference density ratio of mobile 0 can then be given by

$$\begin{aligned} \frac{E_b}{I_0} &= \frac{N\left(\sum\limits_{i=0}^{H-1}\varpi_{0,i}\gamma_{0,i}\right)^2}{\left(\frac{\lambda K}{L}-\frac{\lambda}{H}\right)\sum\limits_{i=0}^{H-1}\gamma_{0,i}^2 + \left(\frac{\lambda K}{L}\right)\sum\limits_{i=H}^{L-1}\gamma_{0,i}^2 + \sum\limits_{i=0}^{L-1}\gamma_{0,i}^2} \\ &\approx \frac{N\left(\sum\limits_{i=0}^{H-1}\varpi_{0,i}\gamma_{0,i}\right)^2}{\left(\frac{\lambda K}{L+1}\right)\sum\limits_{i=0}^{L-1}\gamma_{0,i}^2}. \end{aligned} \tag{12}$$

Assume that $g(\mathbf{w_0}) = \sum_{i=0}^{H-1}\varpi_{0,i}\gamma_{0,i}$. From (12), it is obvious that such a scheme $\{\mathbf{w_0^*}\}$ that satisfies $g(\mathbf{w_0^*}) = \max_{\mathbf{w_0}} g(\mathbf{w_0})$ is the best one in which the maximum forward-link capacity can be achieved. It can be proven that, when $\mathbf{w_0} = \mathbf{w_0^*} = ((\gamma_{0,0}^2/\sum_{i=0}^{H-1}\gamma_{0,i}^2)^{1/2},\ldots,(\gamma_{0,H-1}^2/\sum_{i=0}^{H-1}\gamma_{0,i}^2)^{1/2})$, $g(\mathbf{w_0^*}) = \max_{\mathbf{w_0}} g(\mathbf{w_0}) = (\sum_{i=0}^{H-1}\gamma_{0,i}^2)^{1/2}$. Obviously, here, the optimum power allocation scheme requires that the transmission power from each remote antenna in VC 0 is proportional to the channel gain. Substituting $\mathbf{w_0^*}$ into (12) yields

$$\frac{E_b}{I_0} = \frac{N\cdot\sum\limits_{i=0}^{H-1}\gamma_{0,i}^2}{\left(\frac{\lambda K}{L+1}\right)\sum\limits_{i=0}^{L-1}\gamma_{0,i}^2} = \frac{N}{\left(\frac{\lambda K}{L+1}\right)}\cdot\frac{\sum\limits_{i=0}^{H-1}\gamma_{0,i}^2}{\sum\limits_{i=0}^{L-1}\gamma_{0,i}^2}. \tag{13}$$

Let δ be the E_b/I_0 value required to achieve the level of performance. Then, the outage probability is given by

$$\begin{aligned} P_{\text{out}} &= P_r\left(\frac{E_b}{I_0} < \delta\right) \\ &= P_r\left(I > \frac{N}{\delta\left(\frac{\lambda K}{L+1}\right)} - 1\right) \end{aligned} \tag{14}$$

where $I = \sum_{i=H}^{L-1}(1/\sum_{j=0}^{H-1}(\gamma_{0,j}^2/\gamma_{0,i}^2))$. Unlike the reverse-link case, the distribution of I cannot be regarded as Gaussian, since, here, we have not enough independent random variables. Therefore, we resort to Monte Carlo simulations to estimate P_{out}. The simulation results are presented and discussed in Section V.

V. Numerical Results and Discussions

Consider a three-tier cellular model, which means that $L = 37$. We assume that the voice activity factor λ is 0.375 and the spreading factor N is 127. The standard variance σ_s of the log-normal shadowing variable is 8 dB. As noted in [11], adequate performance (BER $< 10^{-3}$) is achieved with $E_b/I_0 = 7$ dB. Thus, δ is assumed to be 7 dB. The path loss exponent α is 4.

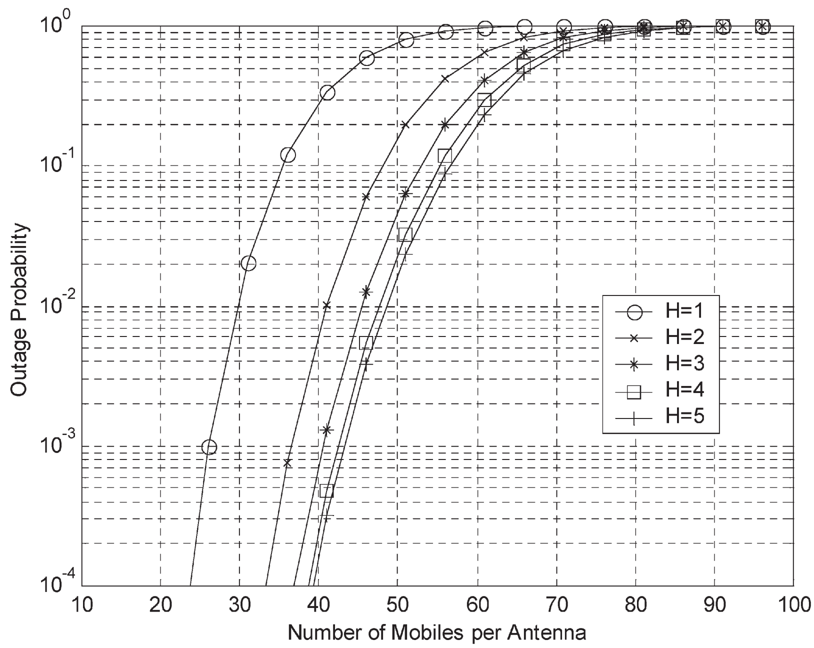
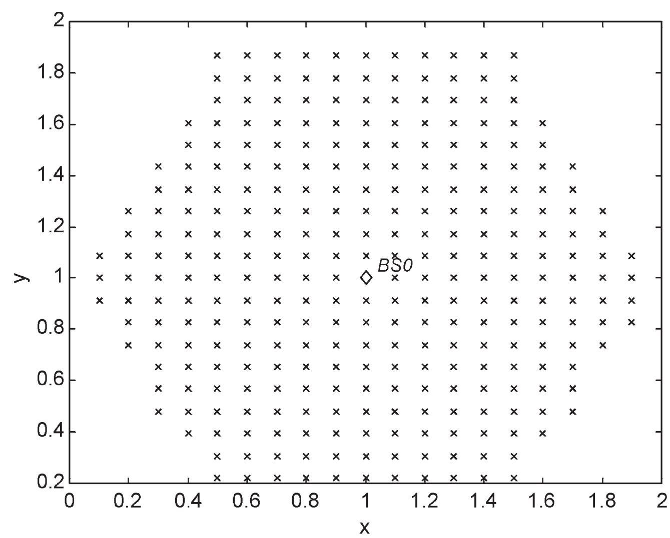


Fig. 2. Reverse-link outage probability versus the number of mobiles per antenna in shadowed Rayleigh environment.

For the reverse link, the outage probability can be calculated using (6), and the results under different values of H are shown in Fig. 2. It is clear that in CDMA DAS, with MRC-based macrodiversity, the reverse-link capacity increases rapidly with the number of antennas in a virtual cell. However, the increase in capacity is convergent. The benefits become very slight when the number of antennas in a virtual cell increases to a certain extent. Therefore, too many receive antennas are not necessary and $H = 4$ is enough.

Moreover, as we know, in traditional cellular CDMA systems (without macrodiversity $H = 1$), the reverse-link performance does not vary with the location of the desired mobile if perfect power control scheme is adopted. In CDMA DAS, the channel gain between the desired mobile and its virtual cell becomes a vector instead of a scalar and each component is independent. Therefore, when mobile 0 moves, the received signal vector also changes in spite of perfect power control.[4] This implies that the received SIR depends on the location of mobile 0. Fig. 3 shows the curves of outage probability versus the location of mobile 0 in the hexagonal coverage zone of an involved remote antenna when $H = 2$ and the number of mobiles per antenna is 32. It can be seen that the outage probability becomes smaller and smaller when mobile 0 moves from the involved remote antenna to the boundary. This indicates that better performance can be obtained on the boundary thanks to higher diversity gains. Mobile 0 can make the best use of benefits from multiple receive antennas there.

For the forward link, the outage probability with the new transmission scheme can be obtained based on (14). The forward-link performance also depends on the location of mobile 0. However, the worst performance is obtained on the



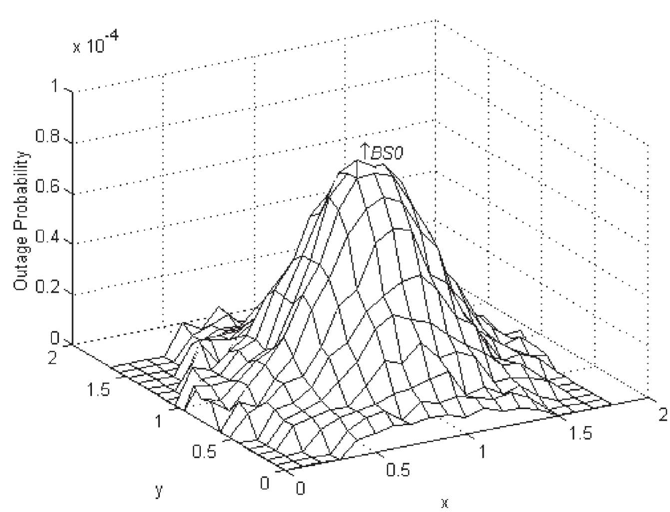


Fig. 3. Reverse-link outage probability versus the location of mobile 0 when $H = 2$ and the number of mobiles per antenna is 32.

[4]It can be illustrated more clearly if we assume that $\mathbf{a}$ and $\mathbf{b}$ are both $H \times 1$ vectors. With perfect power control, we have $\|\mathbf{a}\| = \|\mathbf{b}\|$, while we cannot say that $\mathbf{a} = \mathbf{b}$.

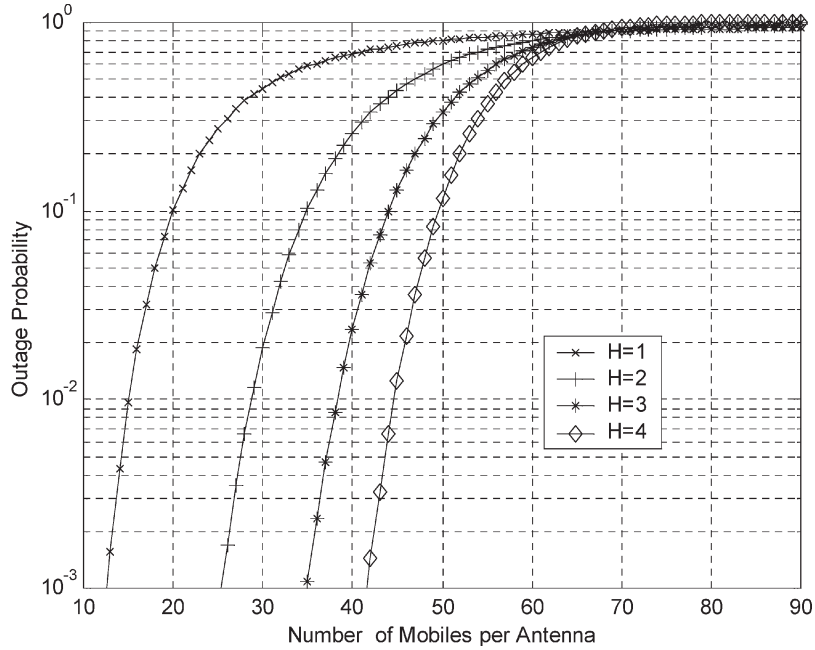


Fig. 4. Forward-link outage probability of the new transmission scheme versus the number of mobiles per antenna in shadowed Rayleigh environment.

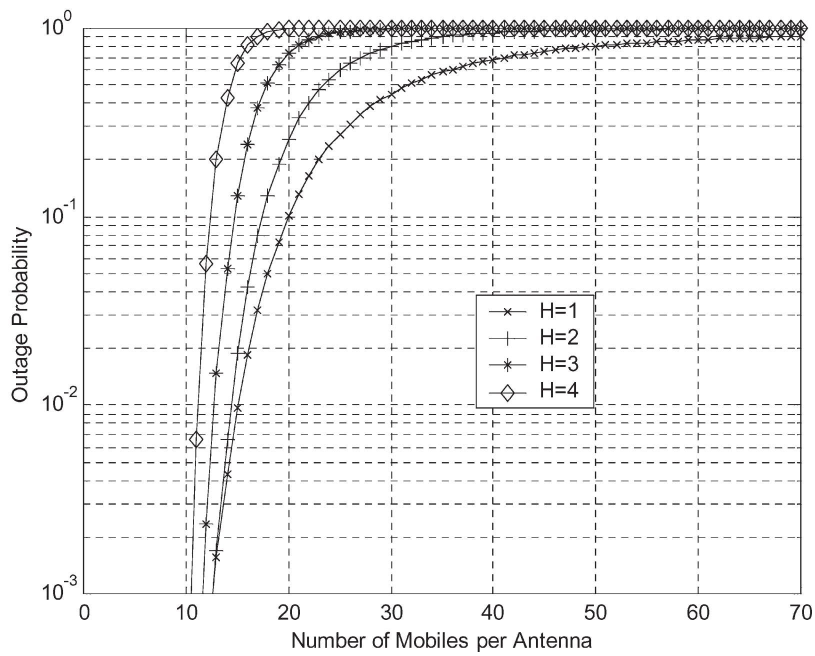


Fig. 5. Forward-link outage probability of the traditional transmission scheme versus the number of mobiles per antenna in shadowed Rayleigh environment.

boundary, not near the involved antenna. Thus, we assume that mobile 0 is located on the boundary and simulate the interference I for 50 000 runs. With the generated histograms of I, we can estimate the outage probability and the results are summarized in Fig. 4. It is clear that with the new transmission scheme, the forward-link capacity increases greatly with the number of antennas in a virtual cell. We also plot the curves of outage probability with the traditional transmission scheme if we allocate equal transmission power among the involved antennas, as shown in Fig. 5. Obviously, the capacity decreases rapidly as H increases. Actually, as proven in Section IV, with the traditional transmission scheme, whatever power allocation scheme is adopted, the capacity cannot increase with H. Selective transmission achieves the maximum forward-link capacity.

VI. Conclusion

We have presented an analytical model for CDMA DAS and derived the outage probability expressions for both the reverse link and the forward link. The effect of maximal ratio combining MRC-based macrodiversity on the reverse-link capacity and the forward-link capacity was investigated, and it was found that the reverse-link capacity increases greatly with the number of antennas in a virtual cell, and the performance depends on the location of the desired mobile. On the forward link, we proved that with the traditional transmission scheme, the forward-link capacity cannot be improved as the number of involved remote antennas increases. Selective transmission achieves the maximum forward-link capacity. After analyzing the cause of capacity loss, we presented a new transmission scheme with which the capacity can be increased greatly if the transmission power is allocated to be proportional to the channel gain.

It should be pointed out that in spite of superior performance, this new transmission scheme requires a complicated adjustment of signal phase and timing and, thus, may lead to higher system complexity than the traditional one. Therefore, the combination of selective transmission scheme and this new one may be more attractive. The former can be applied to the high-mobility and low-data-rate services and the latter is more suitable for the low-mobility and high-data-rate services.

APPENDIX

Assume that $X = \sum_{n=1}^{N} Y_n$, where N is a Poisson random variable and $\{Y_n\}$ is a group of independent identically distributed (i.i.d.) discrete random variables. In [13], it has been proven that

$$E[X] = E[N] \cdot E[Y], \quad \mathrm{Var}[X] = E[N] \cdot E[Y^2]. \tag{15}$$

For all k, arrange $\{\varpi_{k,l_{k,0}}, \ldots, \varpi_{k,l_{k,H-1}}\}$ in a descending order. Let $\mathbf{w}'_{\mathbf{k}} = (\varpi'_{k,0}, \ldots, \varpi'_{k,H-1})$ represent the arranged result, namely, $\mathbf{w}'_{\mathbf{k}}$ satisfies $\varpi'_{k,0} \geq \varpi'_{k,1} \geq \cdots \geq \varpi'_{k,H-1}$, and $\sum_{i=0}^{H-1} (\varpi'_{k,i})^2 = 1$. Then, since $P(\varpi_{m_i,i} = \varpi'_{m_i,j}) = 1/H$, for $j = 0, 1, \ldots, H-1$ and $i = 0, 1, \ldots, L-1$, we have

$$E\left[(\varpi_{m_i,i})^2\right] = \sum_{j=0}^{H-1} \left(\varpi'_{m_i,j}\right)^2 \cdot \frac{1}{H} = \frac{1}{H}. \tag{16}$$

Besides, all the mobiles are assumed to be uniformly distributed. Therefore, $\forall i \in \{0, \ldots, L-1\}$

$$E[K_i] = \frac{HK}{L}. \tag{17}$$

Assume that $\xi_{m_i} = (\psi_{m_i} \varpi_{m_i,i})^2$. Obviously, $\{\xi_{m_i}\}$ is a group of i.i.d. discrete random variables and K_i has a Poisson distribution. By combining (16) and (17) and applying (15), it can be derived that

$$E\left[\sum_{m_i=0}^{K_i-1} \xi_{m_i}\right] = E[K_i] \cdot E[\xi_{m_i}] = \frac{\lambda K}{L}$$

$$\text{and} \quad \mathrm{Var}\left[\sum_{m_i=0}^{K_i-1} \xi_{m_i}\right] = E[K_i] \cdot E\left[\xi_{m_i}^2\right] = \frac{HK}{L} \cdot \mu. \tag{18}$$

Furthermore, we know that

$$\begin{aligned} \mu &= E\left[\xi_{m_i}^2\right] \\ &= E\left[\psi_{m_i}^4\right] \cdot E\left[\varpi_{m_i,i}^4\right] \\ &= \lambda \cdot \left(\sum_{j=0}^{H-1} \left(\varpi'_{m_i,j}\right)^4 \cdot \frac{1}{H}\right) \\ &\leq \lambda \cdot \left(\sum_{j=0}^{H-1} \left(\varpi'_{m_i,j}\right)^2 \cdot \frac{1}{H}\right) \\ &= \frac{\lambda}{H}. \end{aligned} \tag{19}$$

Substituting (19) into (18) yields

$$\frac{\sqrt{\mathrm{Var}\left[\sum\limits_{m_i=0}^{K_i-1} \xi_{m_i}\right]}}{E\left[\sum\limits_{m_i=0}^{K_i-1} \xi_{m_i}\right]} = \frac{\sqrt{\frac{HK}{L} \cdot \mu}}{\frac{\lambda K}{L}} \leq \frac{1}{\sqrt{\frac{\lambda K}{L}}}. \tag{20}$$

Therefore, (9) can be obtained. ■

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