Capacity with MRC-based Macrodiversity in CDMA Distributed Antenna Systems

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***Abstract*-In this paper we analyze the effect of MRC-based macrodiversity on the reverse-link and forward-link capacity in CDMA distributed antenna systems. A detailed analytical model is presented and exact outage probability expressions are derived. Our investigation shows that on the reverse link, with macrodiversity the interference can be suppressed greatly, which leads to a significant increase of capacity. However, on the forward-link, we prove that if simulcasting is used in CDMA distributed antenna systems, the forward-link capacity cannot increase with macrodiversity whatever power allocation scheme is adopted.**

I INTRODUCTION

Interest in distributed antenna system has grown rapidly over the last decade. It was first introduced to solve the problem of coverage for indoor radio communications and applied to DS-CDMA systems recently. In distributed antenna systems, 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]. Thus the demands of a global coverage and large capacity as well as low operation and maintenance costs can be satisfied.

In distributed antenna systems, with remote antennas, each mobile can communicate with multiple antennas simultaneously wherever it is in the system. Thus macrodiversity gain can be obtained to increase the coverage area and compensate for the signal distortion caused by shadowing fading. We can even remove the present cellular structure [2] and divide cells not geographically, but according to the user needs [3]. We call the cell "virtual cell". In particular, the remote antennas serving for mobile i make up the i-th virtual cell. When mobile i moves, the remote antennas in the i-th virtual cell will be dynamically modified to adapt to the changes of mobile i. 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. Obviously much better performance can be achieved with the virtual cell thanks to more flexible resource allocation.

The concept of distributed antenna system is not new. However, most of the previous papers only provide the performance analysis based on the simulation model instead of an analytical one, and fast fading is seldom considered [1]-[4]. In this paper, we made a detailed analytical CDMA distributed antenna system model and derived the outage probability expressions on the reverse link and the forward link. Both fast fading and log-normal shadowing fading are considered. We assume that on the reverse link all the desired signals received by antennas in a virtual cell are combined with maximal ratio combining (MRC), and on the forward link the antennas in a virtual cell simulcast the same signals to the desired mobile, that is, no space-time coding is used. The conventional matched filters are adopted at BS and mobiles instead of multiuser detectors.

For the reverse link, actually we aim to analyze the effect of MRC-based macrodiversity on the reverse-link capacity. We present an analytical reverse link model with MRC-based macrodiversity and show that the capacity increases greatly with the number of antennas in a virtual cell.

The main problem comes in with the forward link. As we know, the reverse link is commonly considered to limit the CDMA system capacity. However, with the emergence of asymmetric wireless data services, the forward-link performance is becoming increasingly important. For the forward link, if multiple antennas transmit signals to a certain mobile, the total interference also increases in spite of the enhanced received signal power due to the additional forward-link channels supported by the involved antennas. Thus macrodiversity doesn't always bring benefits to the forward link as it does to the reverse link. In this paper we prove that whatever power allocation scheme is adopted, the forward-link capacity won't increase with the number of antennas in a virtual cell. In other words, macrodiversity cannot improve the forward-link capacity if simulcasting is used in CDMA distributed antenna systems.

The remainder of this paper is organized as follows. In Section II, our system model is described and the outage probability expressions on the reverse link and the forward link are derived. Numerical results are presented and discussed in Section III. Finally, some concluding remarks are given in Section IV.

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II SYSTEM MODEL

Consider a CDMA distributed antenna system with L remote antennas. These antennas are placed evenly and symmetrically. We assume that totally K mobiles are uniformly distributed in the system and each mobile has its own virtual cell that consists of H remote antennas. We assume that MRC and conventional matched filter are adopted both at the BS and every mobile. The effect of thermal noise is ignored in the interference-limited environment and the channel is assumed to be frequency non-selective.

A *Reverse-Link Capacity*

Assume that with perfect instantaneous power control, after being combined the desired signal power received by each mobile's virtual cell is equal to P'.

Then the received signal of the antennas in the virtual cell of mobile 0[1] 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 P_i is the transmission power of mobile i. ψ_i is a Bernoulli variable with probability of success λ that models the voice activity of mobile i. $\mathbf{S_i(t)}$ is an $H \times H$ diagonal matrix with the diagonal element

$$s_{j,j}(t) = b_i\left(\left\lfloor \frac{t-\tau_{i,j}}{T} \right\rfloor\right) c_i(t-\tau_{i,j}), j = 0,1, \ldots H\text{-}1,$$

where $b_i(\cdot)$ is the transmitted bit of mobile i in duration T and $c_i(\cdot)$ is the spreading code used by mobile i. $\tau_{i,j}$ is the propagation delay from the j-th antenna in VC 0 to mobile i. $\boldsymbol{\gamma}_i$ is an $H \times 1$ vector which represents the channel gain between mobile i and each antenna in VC 0, where $\gamma_{i,j} = \sqrt{r_{i,j}^{-\alpha}} \cdot \beta_{i,j}$. $r_{i,j}$ is the distance from mobile i to the j-th antenna in VC 0 and α is the path-loss exponent. $\beta_{i,j}$ is a complex random variable that represents the corresponding amplitude fade along the path, that is, $|\beta_{i,j}|$ has a Rayleigh or Rice distribution and its mean square value $E\{|\beta_{i,j}|^2\}$ is a log-normal random variable with zero mean and variance σ_s^2. $\mathbf{n(t)}$ is the thermal noise vector.

The output vector of the matched filters is

$\mathbf{Y(l)} = (Y_0(l), Y_1(l), \cdots, Y_{H-1}(l))^T$, where

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

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

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

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

All the output branches are combined with MRC and then we have

$$z(l) = \boldsymbol{\gamma}_0^* \mathbf{Y(l)} = N\sqrt{P_0} b_0(l) \boldsymbol{\gamma}_0^* \boldsymbol{\gamma}_0 + \sum_{i=1}^{K-1} \psi_i \boldsymbol{\gamma}_0^* \mathbf{I_i(l)} + \boldsymbol{\gamma}_0^* \mathbf{n_T(l)} \tag{2}$$

$$= z_0(l) + z_1(l) + z_2(l)$$

where N is the spreading factor (processing gain), * represents complex conjugate transpose and $\mathbf{I_i(l)} = (I_{i0}(l), I_{i1}(l), \cdots, I_{iH-1}(l))^T$.

Similar to [6], it can be derived that

$$Var(z_0(l)) = N^2 P_0 \|\boldsymbol{\gamma}_0^* \boldsymbol{\gamma}_0\|^2, \quad Var(z_1(l)) = N \sum_{i=1}^{K-1} \psi_i P_i \|\boldsymbol{\gamma}_0^* \boldsymbol{\gamma}_1\|^2.$$

According to the power control scheme, we have

$\dfrac{P_0}{P_i} = \dfrac{P'/\|\boldsymbol{\gamma}_0\|^2}{P'/\|\boldsymbol{\gamma}_{1_i}\|^2} = \dfrac{\|\boldsymbol{\gamma}_{1_i}\|^2}{\|\boldsymbol{\gamma}_0\|^2}$, where $\boldsymbol{\gamma}_{1_i}$ represents the channel gain vector between mobile i and each antenna in its own virtual cell.

Then ignoring the thermal noise, the bit energy-to-interference density ratio can be written as

$$\frac{E_b}{I_0} = \frac{N^2 P_0 \|\boldsymbol{\gamma}_0^* \boldsymbol{\gamma}_0\|^2}{N \sum_{i=1}^{K-1} \psi_i P_i \|\boldsymbol{\gamma}_0^* \boldsymbol{\gamma}_1\|^2} = \frac{N}{\sum_{i=1}^{K-1} \psi_i \frac{\|\boldsymbol{\gamma}_0^* \boldsymbol{\gamma}_1\|^2}{\|\boldsymbol{\gamma}_0\|^2 \|\boldsymbol{\gamma}_{1_i}\|^2}} \tag{3}$$

Let δ be the E_b/I_0 value required to achieve the level of performance, then the outage probability is

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

where $I = \sum_{i=1}^{K-1} \psi_i \xi_i$, $\xi_i = \dfrac{\|\boldsymbol{\gamma}_0^* \boldsymbol{\gamma}_1\|^2}{\|\boldsymbol{\gamma}_0\|^2 \|\boldsymbol{\gamma}_{1_i}\|^2}$.

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 $\sigma_I^2 = (K-1) \cdot Var(\psi_i \xi_i) = (K-1) \cdot [\lambda(\mu_\xi^2 + \sigma_\xi^2) - \lambda^2 \mu_\xi^2]$, where μ_ξ and σ_ξ^2 are the mean and variance of ξ_i.

Finally, we have $P_{out} = Q\left(\dfrac{N/\delta - \mu_I}{\sigma_I}\right)$, (4)

where $Q(x) = \dfrac{1}{\sqrt{2\pi}} \int_x^\infty e^{-y^2/2} dy$.

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

B Forward-Link Capacity

Now consider the forward-link capacity. Suppose 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. Because each signal from the involved 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 i-th antenna in VC k and $\varpi_{k,l_{k,i}}$ represents the weight, and we have

$$\forall k,\ \sum_{i=0}^{H-1} \varpi_{k,l_{k,i}}^2 = 1 \cdot$$

Assume that the antennas in VC 0 are numbered 0 to H-1, then the received signal of mobile 0 is

$$x(t) = \sum_{i=0}^{L-1} \sum_{m_i=0}^{K_i-1} \psi_{m_i} \sqrt{P} \varpi_{m_i,i} \gamma_{0,i} b_{m_i} \left(\left\lfloor \frac{t-\tau_{0,i}}{T} \right\rfloor \right) c_{m_i}(t-\tau_{0,i}) + \sum_{i=0}^{L-1} \sqrt{P} \gamma_{0,i} b_i^{'} \left(\left\lfloor \frac{t-\tau_{0,i}}{T} \right\rfloor \right) c_i^{'}(t-\tau_{0,i}) + n(t) \tag{5}$$

where K_i is the number of mobiles that communicate with 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.

Regarding the signals from different antennas in VC 0 as multiple paths of the desired signal, we can separate the paths with a RAKE receiver and the j-th branch is

$$\begin{aligned} y_j(l) &= N\sqrt{P} b_0(l) \varpi_{0,j} \gamma_{0,j} + \sqrt{P} \sum_{\substack{i=0 \\ i \neq j}}^{H-1} \varpi_{0,i} \gamma_{0,i} I_{i,j}(l) \\ &+ \sqrt{P} \sum_{i=0}^{H-1} \sum_{m_i=1}^{K_i-1} \psi_{m_i} \varpi_{m_i,i} \gamma_{0,i} I_{m_i,j}(l) + \sqrt{P} \sum_{i=H}^{L-1} \sum_{m_i=0}^{K_i-1} \psi_{m_i} \varpi_{m_i,i} \gamma_{0,i} I_{m_i,j}(l) \\ &+ \sqrt{P} \sum_{i=0}^{L-1} \gamma_{0,i} I_{i,j}^{'}(l) + n_T(l) \\ &= z_0(l) + z_1(l) + z_2(l) + z_3(l) + z_4(l) + n_T(l) \end{aligned} \tag{6}$$

where

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

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

$$I_{i,j}^{'}(l) = \int_{t_{1j}}^{t_{2j}} b_i^{'} \left(\left\lfloor \frac{t-\tau_{0,i}}{T} \right\rfloor \right) c_i^{'}(t-\tau_{0,i}) c_0(t-\tau_{0,j}) dt,$$

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

Then it can be derived that

$$Var(z_0(l)) = N^2 P (\varpi_{0,j}\gamma_{0,j})^2,\ Var(z_1(l)) = NP \sum_{\substack{i=0 \\ i \neq j}}^{H-1} (\varpi_{0,i}\gamma_{0,i})^2,$$

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

$$Var(z_3(l)) = NP \sum_{i=H}^{L-1} \gamma_{0,i}^2 \sum_{m_i=0}^{K_i-1} (\psi_{m_i} \varpi_{m_i,i})^2,\ Var(z_4(l)) = NP \sum_{i=0}^{L-1} \gamma_{0,i}^2 \cdot$$

For a large number of mobiles, the random variable K_i can be approximated by a Possion random variable with the mean KH/L. It can be proved that

$$\lim_{K \to \infty} \frac{\sqrt{Var\left[\sum_{m_i=0}^{K_i-1} (\psi_{m_i} \varpi_{m_i,i})^2 \right]}}{E\left[\sum_{m_i=0}^{K_i-1} (\psi_{m_i} \varpi_{m_i,i})^2 \right]} = 0 \cdot \tag{7}$$

It shows 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 $\lambda K/L$ approximately.

Using MRC we have

$$\frac{E_b}{I_0} \approx \sum_{j=0}^{H-1} \frac{N \cdot (\varpi_{0,j}\gamma_{0,j})^2}{\sum_{\substack{i=0 \\ i \neq j}}^{H-1} (\varpi_{0,i}\gamma_{0,i})^2 + (\lambda K/L + 1) \sum_{i=0}^{L-1} \gamma_{0,i}^2} \approx \frac{N \cdot \sum_{j=0}^{H-1} (\varpi_{0,j}\gamma_{0,j})^2}{(\lambda K/L + 1) \sum_{i=0}^{L-1} \gamma_{0,i}^2} \tag{8}$$

From (8), it is shown that here E_b / I_0 depends on specific power allocation scheme. Once the power allocation scheme is specified, the weight vector $\mathbf{v}_0$ of mobile 0 is determined ($\mathbf{v}_0 = (\varpi_{0,0},\ \varpi_{0,1},\ \cdots,\ \varpi_{0,H-1})$). Then substitute $\mathbf{v}_0$ into (8), the forward-link capacity can be obtained. Therefore, we aim to find the best power allocation scheme in which the maximum forward-link capacity can be achieved.

Suppose $g(\mathbf{v}_0) = \sum_{i=0}^{H-1} (\varpi_{0,i}\gamma_{0,i})^2$, then it can be derived that when $\mathbf{v}_0 = \mathbf{v}_0^* = (0,\cdots,0,1,0,\cdots,0)$, $g(\mathbf{v}_0^*) = \max_{\mathbf{v}_0} g(\mathbf{v}_0) = \gamma_{0,x}^2$, where $\varpi_{0,x} = 1$ and $\gamma_{0,x} = \max\{\gamma_{0,0},\ \gamma_{0,1},\ \cdots,\ \gamma_{0,H-1}\}$.

According to (8), such a scheme $\{\mathbf{v}_0^*\}$ is the best one in

which E_b/I_0 of mobile 0 is maximized and thus the maximum forward-link capacity can be obtained.

Therefore we have

$$\frac{E_b}{I_0}=\frac{N\cdot\gamma_{0,x}^2}{(\lambda K/L+1)\sum_{i=0}^{L-1}\gamma_{0,i}^2} \tag{9}$$

It proves that in various power allocation schemes, the scheme focusing all the transmission power on the antenna that offers the least attenuation is the best. In other words, MRC-based macrodiversity cannot bring benefits to the forward-link capacity if simulcasting is used in CDMA distributed antenna systems. As illustrated in [7], with macrodiversity the received signal power at the mobile is the sum of the power received from each involved antenna. Therefore, if the total power allocated to each mobile is assumed to be a constant, which means that the total interference is fixed, then it is clear that distributing the transmission signal power among several antennas will cause a decrease of the received SIR.

In order to further confirm this conclusion, we take the example of equal power allocation scheme, that is, we allocate the same transmission power among the involved antennas. Then from (8) it can be derived that

$$\frac{E_b}{I_0}=\frac{N}{H\cdot(\lambda K/L+1)}\cdot\frac{\sum_{i=0}^{H-1}\gamma_{0,i}^2}{\sum_{i=0}^{L-1}\gamma_{0,i}^2}$$

Thus the outage probability is

$$P_{out}=P_r\left(\frac{E_b}{I_0}<\delta\right)=P_r\left(\frac{\sum_{i=H}^{L-1}\gamma_{0,i}^2}{\sum_{i=0}^{H-1}\gamma_{0,i}^2}>\frac{N}{\delta\cdot H\cdot(\lambda K/L+1)}-1\right) \tag{10}$$

III Numerical Results and Discussions

Consider a 3-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 [5], adequate performance (BER<10^{-3}) is achieved with E_b/I_0>7 dB. Thus δ is assumed to be 7 dB.

For the reverse link, the outage probability can be calculated using (4). We simulated the capacity in shadowed-Rayleigh and shadowed-Rice environments and the results are summarized in Fig. 1 and Fig. 2. It is shown that in CDMA distributed antenna systems, with MRC-based macrodiversity the reverse-link capacity increases rapidly with the number of antennas in a virtual cell. For example, in Fig. 1, for 10^{-2} outage probability, the capacity goes up for 30 users per antenna for non-macrodiversity case (H=1) to 41 users per antenna when H=2. With the increase of H even higher capacity can be achieved. However, it can be also seen that the increase of capacity is convergent, that is, the growth rate of capacity decreases as H increases. When H changes from 4 to 5, the capacity difference is very slight.

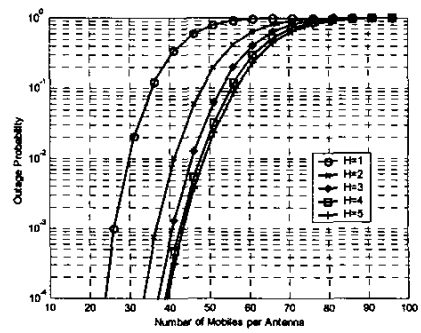

Fig. 1 reverse-link outage probability vs. the number of mobiles per antenna in shadowed-Rayleigh environment, α=4

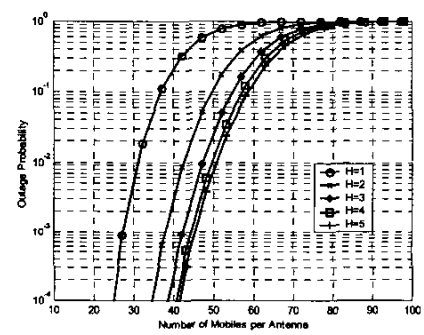

Fig. 2 reverse-link outage probability vs. the number of mobiles per antenna in shadowed-Rice environment, α=4, Rice factor is 4.

The effect of path-loss exponent α on the reverse-link capacity in shadowed-Rayleigh environment is shown in Fig. 3. It can be seen that when α decreases from 4 to 3, the curves shift left, which means that the reverse-link capacity decreases with increasing α. Fig. 4 shows the outage probability in shadowed-Rice environment when Rice factor is 2 and 4. Obviously the capacity increases with increasing Rice factor.

For the forward link, from (10) it can be seen that the distribution of the interference cannot be regarded as Gaussian since here we have not enough independent fading variables. Therefore, we resort to Monte Carlo simulations to estimate P_{out}. We assume that mobile 0 is positioned on the boundary, which represents a worst-case situation. We simulated the outage probability for 50,000 runs. The results

are summarized in Fig. 5. Obviously the capacity decreases rapidly as H increases.

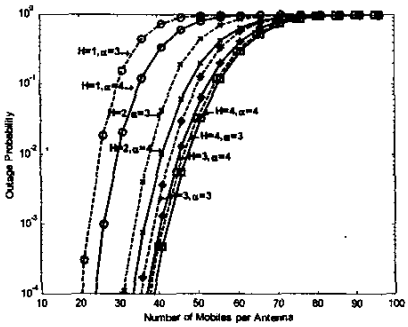

Fig. 3 reverse-link outage probability in shadowed-Rayleigh environment when α is 3 and 4

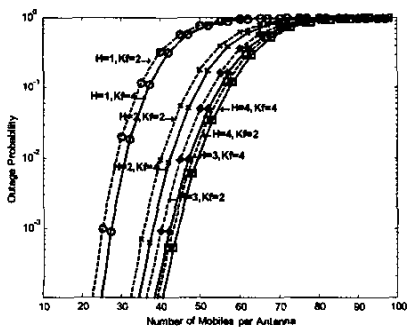

Fig. 4 reverse-link outage probability in shadowed-Rice environment when Rice factor is 2 and 4

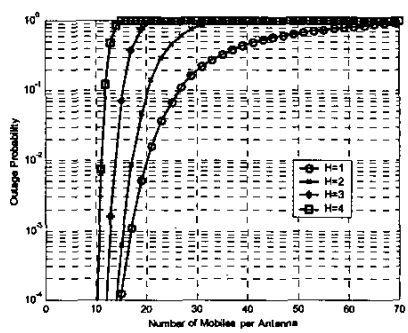

Fig. 5 forward-link outage probability vs. the number of mobiles per antenna with equal power allocation scheme

IV CONCLUSIONS

We have presented an analytical model for CDMA distributed antenna systems and derived the outage probability expressions on both the reverse link and the forward link. We assume that for any mobile, only the antennas in its virtual cell communicate with it, namely, to send the same signals to it on the forward link and receive signals from it on the reverse link. We investigated the effect of MRC-based macrodiversity on the reverse-link capacity and the forward-link capacity and found that, on the reverse link, the capacity increases greatly with the number of antennas in a virtual cell both in shadowed-Rayleigh and shadowed-Rice environments. However, on the forward link, the contrary conclusion is drawn. We proved that the maximum forward-link capacity can be obtained with a single transmission remote antenna, that is, MRC-based macrodiversity causes loss instead of benefits to the forward-link capacity.

It should be pointed out the above conclusions on the forward-link capacity are based on the assumption that all the antennas in a virtual cell transmit the same signals to the mobile. If space-time coding is used, it can be expected that more forward-link capacity might be obtained with multiple transmission antennas than that with a single antenna.

On the reverse link, since no extra interference is generated with multiple remote antennas, the capacity can be increased without complex signal design. However, the benefits are 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.

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