A Comparative Study of the Effects of Microdiversity and Macrodiversity on CDMA Forward-Link Capacity

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Abstract-**Both microdiversity and macrodiversity can effectively overcome the harmful effect of fading. Most of previous work focused on their benefits to the reverse link in CDMA systems. However, their effects on the forward link are less well understood. In this paper, we present an analytical model on forward-link capacity in an H-port macrodiversity system with power control. Maximum Ratio Transmission (MRT) is considered instead of switched selection. We also make a comparison between the performance of microdiversity and macrodiversity on the forward link. The simulation results show that, both types of diversity can bring benefits to the forward-link capacity. However, with macrodiversity higher capacity can be obtained at the cost of complexity.**

I INTRODUCTION

Diversity is an effective means to counteract the harmful effect of channel fading. Macroscopic diversity (macrodiversity) is one kind of diversity to overcome large-scale fading effects [14]. In CDMA systems, combining signals from widely separated base station (BS) antennas allows exploitation of macrodiversity gains. Microscopic diversity (microdiversity) is another type of diversity that can be obtained usually by placing an antenna array at each BS [2]. Since all signals received at the mobile from the same BS propagate through the same path, microdiversity can effectively counteract small-scale multipath fading effects.

The effect of microdiversity on CDMA system performance has been thoroughly studied. Numerous papers show that with antenna arrays both reverse-link capacity[1] and forward-link capacity can be increased greatly [2]-[5]. In contrast, the effect of macrodiversity is not well understood. Most of previous studies focus on the benefits of selection-based macrodiversity (soft handoff) to the reverse link [6]-[10], while the forward-link analysis is less considered. As we know, since multimedia capabilities are ongoing to be introduced into mobile communications, highly asymmetrical services must be provided by the forward link in CDMA systems. Therefore researches on improving CDMA forward-link capacity are becoming more and more necessary. Several authors investigate the performance of macrodiversity on the forward link [11]-[13]. However, [11] and [12] only give the simulation model, and in [13] no power allocation scheme is adopted and only the case of two BS's macrodiversity is studied.

In this paper, we present an analytical model on forward-link capacity with macrodiversity in CDMA systems. We assume that there are *H* BS's that form a macrodiversity group. Different transmit powers are allocated at those BS's in order to maximize the forward-link capacity. Additionally, a comparison is made between the performance of microdiversity and macrodiversity on the forward link. It actually reflects the effect of antenna topology on capacity and can act as a guideline for cell planning. In our analysis, fast fading is assumed not to affect the average power level. Therefore, only the path loss and log-normal shadowing fading are considered.

The forward-link capacity with microdiversity and macrodiversity are analyzed in Section II and Section III, respectively. Numerical results are given in Section IV. Finally, Section V contains our concluding remarks.

II CDMA FORWARD-LINK CAPACITY WITH MICRODIVERSITY

Consider a CDMA forward-link system with coherent demodulation, which is achieved by sending a CDMA pilot with all the traffic channels. The conventional matched filter receiver is adopted at the mobile. We assume that each BS uses a multi-element antenna array to transmit signals to mobiles. Let H be the number of antenna elements ($H>1$). It is well known that with an antenna array, the BS must also beamform on the forward link in order to effectively

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[1] In this paper, 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.

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increase the system capacity. Thus suppose that transmission beamforming can be performed in every BS, that is, signals received from antenna elements in the same BS are cophased at the mobile. The power of the pilot channel is *P*, which is equal to the total allocated power of each mobile. All signals received at the mobile from the same BS propagate over the same path and experience the same fading and path loss. Therefore we assume that the signal power transmitted from each antenna element to a certain mobile is the same, namely, *P/H*. Additionally, as we are concerned with the percentage of capacity change due to the applications of microdiversity and macrodiversity, voice activity and background noises are not considered since they only affect the absolute value of capacity. And the average bit energy-to-interference power spectral density (PSD) ratio is used instead of outage probability.

On these assumptions, for a mobile *k* located in the zeroth cell, the signal power at the output of the matched filter is $S_k = \left(H \cdot \sqrt{\nu_{0k} \cdot P/H}\right)^2 = PH \cdot \nu_{0k}$, where ν_{0k} is the channel gain between the zeroth BS and mobile *k*, and *P* is the total power allocated to mobile *k* from the zeroth BS. The interference power at the output of the matched filter is

$$I_k = \frac{1}{2N} \cdot \sum_{j=1}^{L-1} \nu_{jk} \cdot H \cdot \left(K \cdot \frac{P}{H} + P\right) + \frac{1}{2N} \cdot \nu_{0k} \cdot H \cdot \left[(K-1) \cdot \frac{P}{H} + P\right] \tag{1}$$

where the first term is the intercellular interference from the external *L*-1 surrounding BS's, the second term is the intracellular interference from the other channels in the same cell, *L* is the total number of BS's considered, *N* is the spreading factor (or processing gain), *K* is the number of mobiles per cell and ν_{jk} is the channel gain between the jth BS and mobile *k*.

Then the bit energy-to-interference PSD ratio of mobile *k* is

$$\left(\frac{E_b}{I_0}\right)_k = \frac{PH \cdot \nu_{0k}}{\frac{1}{2N} \cdot \sum_{j=1}^{L-1} \nu_{jk} \cdot H \cdot \left(K \cdot \frac{P}{H} + P\right) + \frac{1}{2N} \cdot \nu_{0k} \cdot H \cdot \left[(K-1) \cdot \frac{P}{H} + P\right]}$$

According to Jensen's inequality, we have

$$E\left[\left(\frac{E_b}{I_0}\right)_k\right] \geq \frac{2N}{\left(\frac{K}{H}+1\right)\left(\sum_{j=1}^{L-1} E\left[\frac{\nu_{jk}}{\nu_{0k}}\right]+1\right)}$$

where the calculation of $\sum_{j=1}^{L-1} E\left[\frac{\nu_{jk}}{\nu_{0k}}\right]$ is referred to [13].

Let $(E_b/I_0)_{req}$ be the required average bit energy-to-interference PSD ratio. It can be derived that a sufficient condition of the required performance is given by

$$\forall k, \quad \frac{2N}{\left(\frac{K}{H}+1\right)\left(\sum_{j=1}^{L-1} E\left[\frac{\nu_{jk}}{\nu_{0k}}\right]+1\right)} \geq \left(\frac{E_b}{I_0}\right)_{req},$$

which is equivalent to

$$K \leq \min_{(x_k, y_k)} \left\{ \left[\frac{2N/\left(\frac{E_b}{I_0}\right)_{req}}{\sum_{j=1}^{L-1} E\left[\frac{\nu_{jk}}{\nu_{0k}}\right]+1} - 1 \right] \cdot H \right\} \tag{2}$$

where $(x_k, \ y_k)$ represents the coordinate of mobile *k*.

Thus the maximum of *K* evaluated from (2) is the minimal number of users that can be supported per cell under the given performance requirement. Then the forward-link capacity with microdiversity is given by

$$C_i = \min_{(x_k, y_k)} \left\{ \left[\frac{2N/\left(\frac{E_b}{I_0}\right)_{req}}{\sum_{j=1}^{L-1} E\left[\frac{\nu_{jk}}{\nu_{0k}}\right]+1} - 1 \right] \cdot H \right\} \tag{3}$$

From (3), it is clear that the forward-link capacity with antenna array of *H* elements increases in proportion to *H*.

III CDMA FORWARD-LINK CAPACITY WITH MACRODIVERSITY

The region area remains the same, while in this case it is divided into *LH* cells and no antenna array is used. We assume that every mobile receives signals from adjacent *H* BS's (*H*>1) and consider the effect of macrodiversity on the forward-link capacity. Similar to the previous section, we suppose that some joint control of the involved BS's to a certain mobile is available so that the signals from the involved BS's are exactly the same with the same spreading code and arrive in phase and simultaneously at the mobile. The power of the pilot channel remains *P*, which is equal to the total allocated power of each mobile. Since the signals from the involved BS's to the mobile undergo different fadings and path loss, some power allocation scheme among the involved BS's should be adopted. Assume that the power allocated to mobile *k* from the ith BS is $\varpi_{ik} \cdot P$, where ϖ_{ik} represents the weight, and we have

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

It should be pointed out that here the power allocation scheme is not the traditional power allocation at the BS transmitter according to the needs of individual mobiles in the given cell [1], but the power allocation among the involved BS's for the given mobile. For every mobile in the system we can adjust its weight vector to achieve the best performance. Besides, the cell area has been reduced to $1/H$ of the original area. To make a fair comparison, here the forward-link capacity should be H times the number of mobiles per cell.

Assume that mobile k communicates with BS 0, 1, ... , H-1. Then the signal power at the output of the matched filter is

$$S_k = \left(\sum_{i=0}^{H-1} \sqrt{\nu_{ik}} \cdot \sqrt{\varpi_{ik} \cdot P} \right)^2 = P \cdot \left(\sum_{i=0}^{H-1} \sqrt{\nu_{ik} \cdot \varpi_{ik}} \right)^2 \qquad (4)$$

The interference power at the output of the matched filter is

$$I_k = \frac{1}{2N} \sum_{j=H}^{LH-1} \nu_{jk} \left(\sum_{m=0}^{K_j-1} p_{jm} + P \right) + \frac{1}{2N} \sum_{j=0}^{H-1} \nu_{jk} \left(\sum_{m=0}^{K_j-2} p_{jm} + P \right) \qquad (5)$$

where K_j represents the number of mobiles that communicate with the jth BS, p_{jm} is the power allocated to mobile m from the jth BS, $j = 0,\ 1,\ \cdots,\ LH-1$, and P is the power of the pilot channel.

It can be proved that for a large number of users, the fluctuation around the mean of the interference generated by each involved BS can be neglected.

Therefore, $\sum_{m=0}^{K_j-1} p_{jm}$ and $\sum_{m=0}^{K_j-2} p_{jm}$ can be replaced by the mean KP and $KP\text{-}P/H$ approximately.

Thus the bit energy-to-interference PSD ratio of mobile k can be derived to be

$$\left(\frac{E_b}{I_0} \right)_k \geq \frac{\left(\sum_{i=0}^{H-1} \sqrt{\nu_{ik} \cdot \varpi_{ik}} \right)^2 \cdot 2N}{(K+1) \sum_{j=0}^{LH-1} \nu_{jk}} \qquad (6)$$

For the specific power allocation scheme, substitute ϖ_{ik} into (6), then the received $(E_b/I_0)_k$ is determined which directly affect the forward-link capacity. Therefore, we aim to find the best scheme to obtain the maximum forward-link capacity.

Suppose that $g\left(\vec{\varpi}_k\right) = \sum_{i=0}^{H-1} \sqrt{\nu_{ik} \varpi_{ik}}$, where $\vec{\varpi}_k = \left(\varpi_{0k},\ \varpi_{1k},\ \cdots,\ \varpi_{H-1,k}\right)$. Then for any mobile k in the system, we can adjust its weight vector $\vec{\varpi}_k$ to $\vec{\varpi}_k^*$, in order that $g\left(\vec{\varpi}_k^*\right) = \max_{\vec{\varpi}_k} g\left(\vec{\varpi}_k\right)$. According to (6), such a scheme $\left\{\vec{\varpi}_k^*\right\}$ is the best one in which the lower bound of the bit energy-to-interference PSD ratio is maximized and thus the maximum forward-link capacity in terms of the minimal number of users per cell can be obtained. It can be proved that, $\forall k$, when

$$\vec{\varpi}_k = \vec{\varpi}_k^* = \left(\frac{\nu_{0k}}{\sum_{i=0}^{H-1} \nu_{ik}},\ \frac{\nu_{1k}}{\sum_{i=0}^{H-1} \nu_{ik}},\ \cdots;\ \frac{\nu_{H-1,k}}{\sum_{i=0}^{H-1} \nu_{ik}} \right),\ \max_{\vec{\varpi}_k} g\left(\vec{\varpi}_k\right) = \sqrt{\sum_{i=0}^{H-1} \nu_{ik}} \qquad (7)$$

From (7), it can be seen that with this power allocation scheme, the transmission power is proportional to the channel gain. Thus a base station with a better link to the mobile would transmit with a higher power.

Substituting (7) into (6) yields

$$\left(\frac{E_b}{I_0} \right)_k \geq \frac{2N \cdot \sum_{i=0}^{H-1} \nu_{ik}}{(K+1) \cdot \sum_{j=0}^{LH-1} \nu_{jk}}$$

Similar to the derivation in section Ⅱ, the sufficient condition of the required performance is given by

$$K \leq \min_{(x_k, y_k)} \left\{ \sum_{i=0}^{H-1} \frac{2N / \left(\frac{E_b}{I_0} \right)_{req}}{\sum_{j=0}^{LH-1} E\left[\frac{\nu_{jk}}{\nu_{ik}} \right]} - 1 \right\}$$

Then the forward-link capacity with H BS's macrodiversity is

$$C_a = \min_{(x_k, y_k)} \left\{ \left[\sum_{i=0}^{H-1} \frac{2N / \left(\frac{E_b}{I_0} \right)_{req}}{\sum_{\substack{j=0 \\ j \neq i}}^{LH-1} E\left[\frac{\nu_{jk}}{\nu_{ik}} \right] + 1} - 1 \right] \cdot H \right\} \qquad (8)$$

Ⅳ NUMERICAL RESULTS AND DISCUSSIONS

Using the analytical results from the previous section, numerical results are presented. We assume that the spreading factor N = 127 and L = 19.

To show the improvement afforded by macrodiversity, curves of forward-link capacity per cell versus $(E_b/I_0)_{req}$ for different values of H and α are plotted in Fig.1. The standard deviation of the shadowing fading random variable σ is assumed to be 8 dB. From Fig.1, it is clear that the forward-link capacity increases with H rapidly. This indicated that with the appropriate power allocation scheme, macrodiversity can bring benefits to the forward-link capacity. On the other hand, it can also be seen that when the path-loss exponent α is reduced from 4 to 3, the capacity falls off.

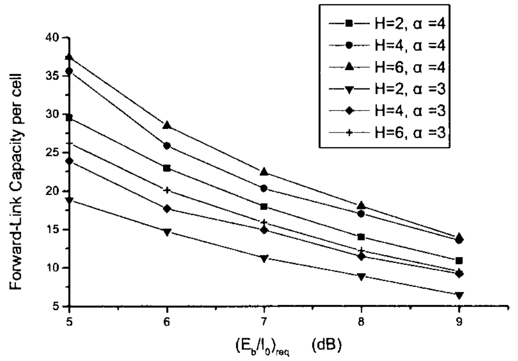

Fig.1. Forward-link capacity with macrodiversity, σ = 8dB

The influence of log-normal shadowing fading on capacity is shown in Fig.2. We know that in a mobile radio environment σ varies from 6 to 12 dB. From Fig.2, it can be concluded that an increase of σ results in the reduction of the forward-link capacity.

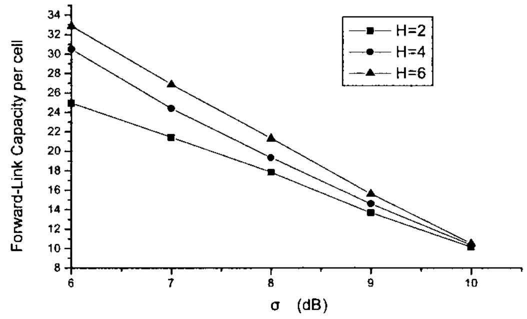

Fig.2. Influence of shadowing on forward-link capacity with macrodiversity. α = 4, $(E_b/I_0)_{req}$ = 7dB

Fig.3 shows a direct comparison of the forward-link capacity with H antennas microdiversity and H antennas macrodiversity when α = 4 and σ = 8dB. Obviously, the capacity increases rapidly with H in both types of diversity. However, as H increases the forward-link capacity with macrodiversity grows faster. This can be attributed to the fact that in the worst case the number of interference sources in the first tier with macrodiversity is less than that with microdiversity. Besides, we also notice that when H=2, the difference of capacity in these two diversity means is very slight.

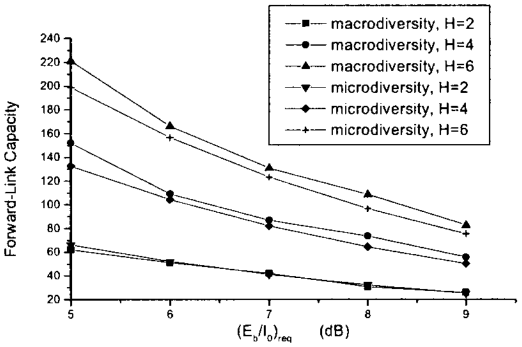

Fig.3. Comparison of the forward-link capacity with microdiversity and macrodiversity. α = 4, σ = 8dB

In Fig.4, it is shown more clearly that H antennas macrodiversity outperforms H antennas microdiversity and the capacity gap becomes wider with the increase of H. Moreover, from (3) and (8), it can be also seen that in capacity formulas, with microdiversity the number of terms influenced by the path-loss exponent α is L-1, while with macrodiversity the number is LH. So the forward-link capacity with macrodiversity is more sensitive to α. It is confirmed via the simulation. From Fig.4, it is shown that though the forward-link capacity in both diversity means falls off when α is reduced to 3, the capacity loss with macrodiversity is greater.

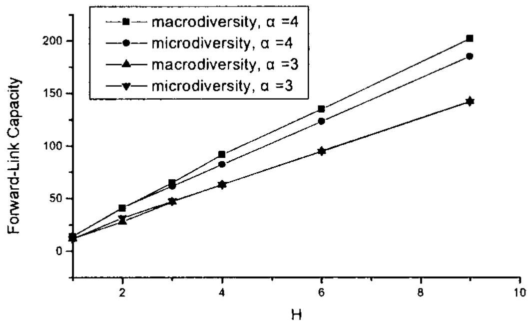

Fig.4. Comparison of the forward-link capacity with microdiversity and macrodiversity. σ = 8dB, $(E_b/I_0)_{req}$ = 7dB

It should be pointed out that with H antennas microdiversity, if orthogonal codes are used, interference will be primarily due to outside cell interference (the second term on the right of (1) becomes zero) and the corresponding forward-link capacity will be increased greatly. However, with H BS's macrodiversity, since different mobile communicates with different BS's, it is difficult to allocate orthogonal codes among the mobiles. Thus capacity enhancement can't be obtained through this approach with macrodiversity. In Fig.5, we plot the forward-link capacity with orthogonal codes in microdiversity and the forward-link capacity without orthogonal codes in microdiversity and macrodiversity

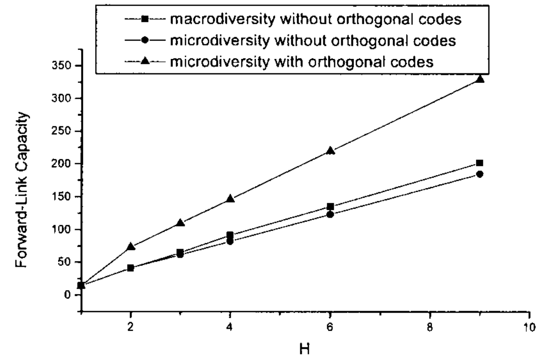

Fig.5. Forward-link capacity with orthogonal codes in microdiversity and without orthogonal codes in microdiversity and macrodiversity. $\alpha = 4$, $\sigma = 8\text{dB}$, $(E_b/I_0)_{req} = 7\text{dB}$

V CONCLUSIONS

We have derived the analytic expression for the forward-link capacity in an H-port macrodiversity system and found the best power allocation scheme to obtain the maximum capacity. We also made a comparison between the forward-link capacity with H antennas microdiversity and H antennas macrodiversity. The numerical results show that the forward-link capacity increases with H in both types of diversity, while with macrodiversity more benefits can be brought.

It should be pointed out that, in spite of more capacity improvement gained with macrodiversity in comparison with microdiversity, the system complexity is also higher. With microdiversity, signals from the same BS arrived at the mobile in phase and simultaneously after they propagate through the same path. However, with macrodiversity a more complex adjustment of signal phase and signal timing is necessary as the involved BS's are widely separated. Additionally, with microdiversity the capacity can be increased greatly if orthogonal codes are adopted, while such codes are difficult to be applied to macrodiversity.

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