

# Effect of Macrodiversity on CDMA Forward-Link Capacity

Lin Dai, Shi-dong Zhou, Yan Yao

State Key Lab on Microwave & Digital Communications  
Tsinghua University, Beijing, CHINA, 100084

**Abstract**—Macrodiversity is an effective means to overcome large-scale fading effects. Much of previous work focused on its benefits to the reverse link in CDMA systems. However, its effect on the forward link is less well understood. In this paper, we analyze the CDMA forward-link capacity with macrodiversity and the results show that macrodiversity causes forward-link capacity loss whatever power allocation scheme is adopted. Based on the analysis of the cause of capacity loss, we further present a new transmission scheme, in which some joint control among the involved base stations is made to assure that the signals arrived at the desired mobile in phase and simultaneously. The simulation results show that in the new transmission scheme much higher capacity can be achieved with macrodiversity and the capacity increases rapidly with the number of involved base stations.

## I INTRODUCTION

Diversity is an effective means to counteract the harmful effect of channel fading. It includes macroscopic diversity (macrodiversity) and microscopic diversity (microdiversity) [4]. Macrodiversity is often used to overcome large-scale fading effects. In CDMA systems, combining signals from widely separated base station (BS) antennas allows exploitation of macrodiversity gains. It has been proved that macrodiversity can improve the reverse-link quality, extend the cell coverage and increase the reverse-link capacity<sup>1</sup> [2][5][6]. However, to the forward link, macrodiversity doesn't always bring benefits as it does to the reverse link. Despite the enhanced received signal power, the total interference also increases due to the additional forward-link channels supported by the involved BS's. The effect of soft handoff (two BS's macrodiversity) on the forward-link capacity in CDMA systems is investigated in [3] and the conclusion shows that, soft handoff causes capacity loss which increases as the handoff zone increases. Nevertheless, its focus is on the effect of

handoff zone on capacity and only the case of two BS's macrodiversity is studied.

In fact, with macrodiversity the forward-link capacity depends on many factors, such as the number of involved BS's and the specified power allocation scheme. Therefore, we analyze the case of multiple BS's macrodiversity and find that, whatever power allocation scheme is adopted, the forward-link capacity won't increase with the number of involved BS's. Based on the analysis, we further present a new transmission scheme in which some joint control among the involved BS's is made to assure that the signals arrived at the desired mobile in phase and simultaneously. It is proved that in this case a power allocation scheme can be found in which the received SIR is improved as the number of involved BS's increases. In other words, in the new transmission scheme macrodiversity can bring benefits instead of loss to the forward-link capacity in CDMA systems.

In this paper, the effects of macrodiversity on CDMA forward-link capacity in traditional and new transmission schemes are analyzed. Fast fading is assumed not to affect the average power level. Therefore, only the path loss and slow fading are considered

In the next section, the effect of macrodiversity in traditional transmission scheme is analyzed and based on the analysis, a new transmission scheme is presented in Section III. Finally, Section IV contains our concluding remarks.

## II CDMA FORWARD-LINK CAPACITY WITH MACRODIVERSITY IN TRADITIONAL TRANSMISSION SCHEME

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. Suppose that every mobile receives signals from adjacent  $H$  BS's ( $H > 1$ ) wherever it is in the system. The power of the pilot channel is  $P$ , which is equal to the total allocated power of each mobile. Since each signal from the involved BS's to a

<sup>1</sup> 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.

certain mobile propagates through a distinct path and arrives at the mobile with independent fading, some power allocation scheme among the involved BS's should be adopted. Assume that the power allocated to mobile  $k$  from the  $i$ th BS is  $\varpi_{ik} \cdot P$ , where  $\varpi_{ik}$  represents the weight, and we have

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

(Let us number the involved BS's according to the descending order of their channel gains, that is, the BS that offers the least signal attenuation to mobile  $k$  is number 0 with the weight  $\varpi_{0k}$ , and so on.) 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. The mobile receiver has  $H$ -matched filters to detect the  $H$  signals from its  $H$  BS's and the outputs of the  $H$ -matched filters are cophased and combined through the Maximal Ratio Combiner. Additionally, as we are concerned with the percentage of capacity change due to the application of 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 rate.

Suppose mobile  $k$  receives signals from BS 0, 1, ...  $H-1$ , the signal power at the output of the  $i$ th matched filter is  $S_{ik} = v_{ik} \cdot \varpi_{ik} P$ , where  $v_{ik}$  is the channel gain between the  $i$ th BS and mobile  $k$ . The interference power at the output of the  $i$ th matched filter is

$$I_{ik} = \frac{1}{2N} \sum_{j=0, j \neq i}^{L-1} v_{jk} \left( \sum_{m=0}^{K_j-1} p_{jm} + P \right) + \frac{1}{N} \cdot v_{ik} \cdot \left( \sum_{m=0}^{K_i-2} p_{im} + P \right)$$

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),  $v_{jk}$  is the channel gain between the  $j$ th BS and mobile  $k$ ,  $K_j$  represents the number of mobiles that communicate with the  $j$ th BS,  $p_{jm}$  is the power allocated to mobile  $m$  from the  $j$ th BS,  $j=0, 1, \dots, L-1$ , and  $P$  is the power of the pilot

channel. The intercellular interference is reduced by factor of two due to the carrier incoherence.

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  $\sum_{m=0}^{K_i-2} p_{im}$  can be replaced by

the mean  $KP$  and  $KP-P/H$  approximately, where  $K$  is the number of mobiles per cell.

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

$$\left( \frac{E_b}{I_0} \right)_k = \sum_{i=0}^{H-1} \left( \frac{E_b}{I_0} \right)_{ik} \geq \sum_{i=0}^{H-1} \frac{v_{ik} \cdot \varpi_{ik} \cdot 2N}{(K+1) \cdot \left( \sum_{j=0, j \neq i}^{L-1} v_{jk} + 2 \cdot v_{ik} \right)} \quad (1)$$

According to Jensen's inequality, we have

$$E \left[ \left( \frac{E_b}{I_0} \right)_k \right] \geq \sum_{i=0}^{H-1} \frac{2N}{(K+1) \cdot E \left[ \sum_{j=0, j \neq i}^{L-1} \frac{v_{jk}}{v_{ik}} \cdot \frac{1}{\varpi_{ik}} + 2 \cdot \frac{1}{\varpi_{ik}} \right]}$$

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

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

which is equivalent to

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

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.

According to specific power allocation scheme,  $\varpi_{ik}$  can be determined. Substitute  $\varpi_{ik}$  into (2), then the forward-link capacity with macrodiversity can be obtained. Take the example of equal power allocation scheme. For any mobile  $k$  in the system, suppose  $\forall i = 0, 1, \dots, H-1$ ,  $\varpi_{ik} = 1/H$ . Then the forward-link capacity with  $H$  BS's macrodiversity can be evaluated by

$$C_e = \min_{(x_k, y_k)} \left\{ \frac{\sum_{i=0}^{H-1} \frac{2N / \left( \frac{E_b}{I_0} \right)_{req}}{\sum_{j=0, j \neq i}^{L-1} E \left[ \frac{v_{jk}}{v_{ik}} \right] + 2} \cdot \frac{1}{H} - 1 \right\} \quad (3)$$

As we know, adequate performance ( $BER \leq 10^{-3}$ ) is achievable on the forward link with  $E_b/I_0 \geq 7dB$ . Consequently, given  $(E_b/I_0)_{req} = 7dB$ ,  $N=127$ ,  $\sigma = 8dB$  ( $\sigma$  is the standard deviation of the shadowing fading random variable) and considering only the first two tiers of interfering cells ( $L=19$ ), the forward-link capacity for different values of the number of involved BS's  $H$  can be calculated using (3). Curves of the capacity are shown in Fig.1 for the path-loss exponent  $\alpha$  of 4 and 3. From Fig.1, it can be concluded that in the equal power allocation scheme, macrodiversity brings capacity loss that increases with  $H$ . However, as  $H$  increases, the reduction rate of the forward-link capacity decreases.

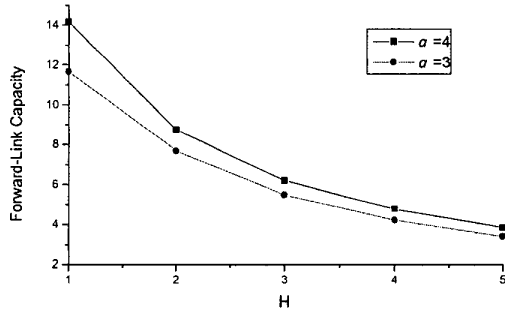


Fig. 1. Forward-link capacity with macrodiversity as a function of  $H$  in equal power allocation scheme in traditional transmission scheme

From the analysis above, it is clear that the

forward-link capacity depends on the specific power allocation scheme. Therefore, we now aim to find the best scheme to obtain the maximum forward-link capacity.

Suppose  $g(\vec{\varpi}_k) = \frac{\sum_{i=0}^{H-1} \varpi_{ik}}{\sum_{j=0, j \neq i}^{L-1} \left[ \frac{v_{jk}}{v_{ik}} \right] + 2}$ , where

$\vec{\varpi}_k = (\varpi_{0k}, \varpi_{1k}, \dots, \varpi_{H-1,k})$ . Then for any mobile  $k$  in

the system, we can adjust its weight vector  $\vec{\varpi}_k$  to  $\vec{\varpi}_k^*$ , in

order that  $g(\vec{\varpi}_k^*) = \max_{\vec{\varpi}_k} g(\vec{\varpi}_k)$ . According to (1), such a

scheme  $\{\vec{\varpi}_k^*\}$  is the best one in which the lower bound of

the bit energy-to-interference PSD ratio of every mobile 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

$$\vec{\varpi}_k = \vec{\varpi}_k^* = (1, 0, \dots, 0), \quad g(\vec{\varpi}_k^*) = \max_{\vec{\varpi}_k} g(\vec{\varpi}_k),$$

and the corresponding forward-link capacity is

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

It proves that in various power allocation schemes, the scheme focusing all the transmission power on the BS that offers the least attenuation is the best. In other words, in traditional transmission scheme, maximum forward-link capacity can be obtained without macrodiversity. Though macrodiversity is an effective means to counteract the channel fading and improve the signal quality, it also causes forward-link capacity loss in this case.

### III CDMA FORWARD-LINK CAPACITY WITH MACRODIVERSITY IN NEW TRANSMISSION SCHEME

In the traditional transmission scheme, the total received signal power at the mobile is the sum of the power received from each involved BS. If the total power allocated to each mobile is a constant, which means that the total interference is fixed, then it is clear that distributing the signal power among several BS's will cause a decrease of received signal power compared with the case without macrodiversity. That's why macrodiversity leads to capacity loss in the traditional transmission scheme.

Based on this analysis, we present a new transmission scheme. In this scheme, all BS's involved transmit the same information to a certain user with the same spreading code. And the phases and timing of the transmitted signals are adjusted to assure that the signals arrive at the mobile receiver in phase and simultaneously. Then 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 BS's 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.

According to the analysis above, assume that mobile  $k$  communicates with BS 0, 1, ...,  $H-1$ . Then the signal power at the output of the matched filter is

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

The interference power at the output of the matched filter is

$$I_k = \frac{1}{2N} \sum_{j=H}^{L-1} v_{jk} \left( \sum_{m=0}^{K_j-1} P_{jm} + P \right) + \frac{1}{2N} \sum_{j=0}^{H-1} v_{jk} \left( \sum_{m=0}^{K_j-2} P_{jm} + P \right) \quad (5)$$

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

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

Similarly, in order to maximize the forward-link capacity, suppose that  $g\left(\vec{\varpi}_k\right) = \sum_{i=0}^{H-1} \sqrt{v_{ik}} \varpi_{ik}$ . Then from

(6) it is obvious that such a scheme  $\left\{ \vec{\varpi}_k^* \right\}$  that satisfies

$g\left(\vec{\varpi}_k^*\right) = \max_{\vec{\varpi}_k} g\left(\vec{\varpi}_k\right)$  is the best one in which the

maximum forward-link capacity can be achieved. It can be proved that,  $\forall k$ , when

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

Substituting (7) into (6) yields

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

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

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

Then the forward-link capacity with  $H$  BS's macrodiversity in the new transmission scheme is

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

The simulation results are summarized in Fig.2.

From Fig.2, it is shown that in this new transmission scheme, macrodiversity brings substantial capacity enhancement if we distribute the signal power of each mobile among its involved BS's in proportion to the

channel gains. However, with  $H$  increasing, the increase rate of the forward-link capacity decreases.

It should be pointed out that in spite of the capacity benefits, the system complexity rises greatly since in the new transmission scheme, for every mobile a joint control is required among all the involved BS's that are widely separated.

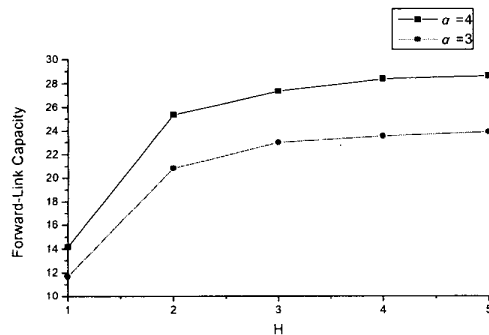


Fig. 2. Forward-link capacity with macrodiversity as a function of  $H$  in the best power allocation scheme in new transmission scheme

#### IV CONCLUSIONS

We have studied the effect of macrodiversity on the forward-link capacity in CDMA systems in two transmission schemes by using an average bit energy-to-interference PSD ratio corresponding to a BER of  $10^{-3}$ . In traditional transmission scheme, we prove that the maximum forward-link capacity can be achieved without macrodiversity. It also means that in this case macrodiversity always causes forward-link capacity loss. The conclusion is confirmed through simulations.

After analyzing the cause of capacity loss, we present a new transmission scheme in which the signals arrive at the mobile in phase and simultaneously. The simulation shows that the forward-link capacity increases rapidly as the number of involved BS's goes up if the transmission power allocated to a certain mobile from each involved BS is proportional to the channel gain between them. In this new transmission scheme, macrodiversity brings tremendous benefits to the forward-link capacity at the cost of system complexity.

It should be pointed out that, in the new scheme, it is required that all the signals from the involved BS's arrive at the mobile in phase and simultaneously on the assumption

of no multipath. However, multipath always exists. So some techniques such as OFDM should be adopted to reduce symbol rate in order to mitigate the effect of multipath as much as possible.

#### REFERENCES

- [1] K. S. Gilhousen et al., "On the capacity of a cellular CDMA system", IEEE Trans. Veh. Technol., vol. 40, pp 303-312, May 1991.
- [2] A. J. Viterbi, Audrey M. Viterbi, Klein S. Gilhousen, and Ephraim Zehavi, "Soft handoff extends CDMA cell coverage and increase reverse link capacity", IEEE Journal On Selected Areas In Commun., vol. 12, pp 1281-1288, Oct. 1994.
- [3] Chin-Chun Lee, and Raymond Steele, "Effect of soft and softer handoffs on CDMA system capacity", IEEE Trans. Veh. Technol., vol. 47, pp 830-841, Aug. 1998.
- [4] W. C. Y. Lee, *Mobile communications engineering: theory and applications*, New York: McGraw-Hill, 1997.
- [5] S.V.Hanly, and D.N.C.Tse, "Resource pooling and effective bandwidths in CDMA networks with multiuser receivers and spatial diversity", IEEE Trans. on Inform.Theory, in press.
- [6] S. V. Hanly, "Capacity and power control in spread spectrum macrodiversity radio networks", IEEE Trans. Commun., vol. 44, pp 247-256, Feb. 1996.
- [7] W.C.Jakes, *Microwave Mobile Radio Communications*, NewYork: IEEE Press, 1974.
- [8] D.J.Lu, *Stochastic Process and its applications*, Beijing: Tsinghua Univ. Press, 1986.