PAPER

Effects of Macrodiversity and Microdiversity on CDMA Forward-Link Capacity

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SUMMARY   Both macrodiversity and microdiversity can effectively overcome the harmful effect of fading. Much 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 analyze the CDMA forward-link capacity with macrodiversity and microdiversity. It is shown that macrodiversity causes forward-link capacity loss since the extra forward-link channels supported by the involved base stations enhance not only the received signal power, but also the total interference. Unfortunately the latter gains more 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. A comparison of the forward-link capacity with microdiversity and macrodiversity indicates 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.

key words: *CDMA, forward-link capacity, macrodiversity, microdiversity*

1. Introduction

Diversity is an effective means to counteract the harmful effect of channel fading. Macroscopic diversity (macrodiversity) is one kind of diversity used to overcome large-scale fading effects [8]. 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 usually be obtained by placing an antenna array at each BS [3]. 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.

It has been proved that in CDMA systems both macrodiversity and microdiversity can improve the reverse-link quality and increase the reverse-link capacity[*] [3]–[7]. Furthermore, it is shown in [3] that under certain conditions the upper bound of the reverse-link capacity with macrodiversity is exactly the same as that with microdiversity. However, their effects on the for-

ward link are not well understood. Though it is proved that with microdiversity the forward-link capacity can be increased several fold [6], the effect of macrodiversity on the forward-link capacity remains unknown. Also, a comparison of the effects of these two types of diversity has not been made yet, although it actually reflects the effect of antenna topology on capacity and can act as a guideline for cell planning. Thus our research object is to establish a fair and reasonable model to investigate the effect of macrodiversity on the forward-link capacity and compare it with that of microdiversity.

As we know, if multiple BS's transmit signals to a certain mobile, then despite the enhanced received signal power, the total interference also increases due to the additional forward-link channels supported by the involved BS's. Thus macrodiversity doesn't always bring benefits to the forward link as it does to the reverse link. The effect of soft handoff (two BS's macrodiversity) on the forward-link capacity in CDMA systems is investigated in [2] 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 arrive 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

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[*]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.

transmission schemes are analyzed. Moreover, we make a comparison of the forward-link capacity with microdiversity and that with macrodiversity in the new transmission scheme.

We assume that fast fading does not affect the average power level. Therefore, only the path loss and log-normal shadowing fading are considered. The channel is assumed to be frequency non-selective, namely, the effect of multipath is not taken into account. Additionally, the average bit energy-to-interference power spectral density (PSD) ratio is used instead of outage probability.

In the next section, we derive the basic formula of forward-link capacity in CDMA systems without diversity. The effects of macrodiversity and microdiversity are analyzed in Sect. 3 and Sect. 4, respectively. In Sect. 5 we present simulation results. Finally, Sect. 6 contains our concluding remarks.

2. Basic Model on CDMA Forward-Link Capacity without Diversity

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. Assume that all the mobiles in each cell are allocated the same power P, which is equal to the power of the pilot channel. As we are concerned with the percentage of capacity change, voice activity and background noise are not considered since they only affect the absolute value of capacity.

Consider a scenario where there are K mobiles uniformly distributed around each BS. For a mobile k located in the zeroth cell, the signal power at the output of the matched filter is

$$S_k = \nu_{0k} \cdot P, \tag{1}$$

where ν_{0k} is the channel gain between the zeroth BS and mobile k, and P is the power allocated to mobile k from the zeroth BS. The interference power at the output of the matched filter is

$$I_k = I_{ext} + I_{\text{int}}$$
$$= \frac{1}{2N} \sum_{j=1}^{L-1} \nu_{jk} \cdot (K+1)P + \frac{1}{N} \cdot \nu_{0k} \cdot KP, \tag{2}$$

where the first term I_{ext} is the intercellular interference from the external $L-1$ surrounding BS's, the second term I_{int} 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 (processing gain), K is the number of mobiles per cell and ν_{jk} is the channel gain between the jth BS and mobile k. The intercellular interference is reduced by factor of two due to the carrier incoherence.

From (1) and (2), the bit energy-to-interference

PSD ratio $(E_b/I_0)_k$ at the output of the matched filter is

$$\left(\frac{E_b}{I_0} \right)_k = \frac{\nu_{0k} \cdot P}{\frac{1}{2N} \sum\limits_{j=1}^{L-1} \nu_{jk} \cdot (K+1)P + \frac{1}{N} \cdot \nu_{0k} \cdot KP}.$$

According to Jensen's inequality[†], we have

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

$$\geq \frac{2N}{(K+1) \cdot \left(\sum\limits_{j=1}^{L-1} E\left[\frac{\nu_{jk}}{\nu_{0k}} \right] + 2 \right)}, \tag{3}$$

where $E[X]$ denotes the expectation of the random variable X.

For a radio channel with path-loss exponent α and a shadowing fading random variable ξ with a standard deviation of σ and zero mean, the effect of path loss and shadowing between mobile k and the jth BS is $\nu_{jk} = r_{jk}^{-\alpha} \cdot 10^{\xi_{jk}/10}$, where r_{jk} is the distance between mobile k and the jth BS, and ξ_{jk} is the i.i.d.[††] Gaussian random variable. $j = 0, 1, \cdots, L-1$.

Then we have

$$\sum_{j=1}^{L-1} E\left[\frac{\nu_{jk}}{\nu_{0k}} \right] = \sum_{j=1}^{L-1} \left(\frac{r_{0k}}{r_{jk}} \right)^{\alpha}$$
$$\cdot E\left[\Phi_j \left(\zeta_j, \quad \frac{r_{0k}}{r_{jk}} \right) \cdot 10^{\zeta_j/10} \right], \tag{4}$$

where $\zeta_j = \xi_{jk} - \xi_{0k}$, and

$$\Phi_j \left(\zeta_j, \quad \frac{r_{0k}}{r_{jk}} \right) = \begin{cases} 1 & \left(\frac{r_{0k}}{r_{jk}} \right)^{\alpha} 10^{\zeta_j/10} \leq 1 \\ 0 & \text{otherwise} \end{cases}$$

is a constraint function, which accounts for the mobiles tending to communicate with the BS that offers the least signal attenuation under fading conditions. From [1], it is proved that

$$E\left[\Phi_j \left(\zeta_j, \quad \frac{r_{0k}}{r_{jk}} \right) \cdot 10^{\zeta_j/10} \right] = \exp \left(\sigma \ln 10/10 \right)^2$$
$$\cdot \left\{ 1 - Q\left[\frac{10\alpha \log \frac{r_{jk}}{r_{0k}}}{\sqrt{2\sigma^2}} - \frac{\sqrt{2\sigma^2} \ln 10}{10} \right] \right\} \tag{5}$$

Substitute (5) into (4), then $\sum\limits_{j=1}^{L-1} E\left[\frac{\nu_{jk}}{\nu_{0k}} \right]$ can be

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[†]Jensen's inequality: If f is convex on an interval I and $x_1, x_2, \cdots x_n$ are in I, then $f\left(\frac{x_1 + x_2 + \cdots x_n}{n} \right) \leq \frac{f(x_1) + f(x_2) + \cdots f(x_n)}{n}$.

Generalized Jensen's inequality: Let f be continuous and convex on an interval I. If $x_1, x_2, \cdots x_n$ are in I and $0 < t_1, t_2 \cdots t_n < 1$ with $t_1 + t_2 + \cdots t_n = 1$, then $f(t_1 x_1 + t_2 x_2 + \cdots t_n x_n) \leq t_1 f(x_1) + t_2 f(x_2) + \cdots t_n f(x_n)$

[††]i.i.d. is the abbreviation of "independent and identical distribution."

calculated.

Let $(E_b/I_0)_{req}$ be the required average bit energy-to-interference PSD ratio. According to (3), for every mobile in the system, if we have

$$\forall k, \quad \frac{2N}{(K+1) \cdot \left(\sum\limits_{j=1}^{L-1} E\left[\frac{\nu_{jk}}{\nu_{0k}} \right] + 2 \right)} \geq \left(\frac{E_b}{I_0} \right)_{req}, \quad (6)$$

then

$$\forall k, \quad E\left[\left(\frac{E_b}{I_0} \right)_k \right] \geq \left(\frac{E_b}{I_0} \right)_{req}, \quad (7)$$

which denotes that the required performance is satisfied.

Therefore, (6) is the sufficient condition of the required performance, and the maximum of K evaluated from (6) is the minimal number of users that can be supported per cell under the given performance requirement.

Furthermore, (6) can be rewritten as

$$\forall k, \quad K \leq \frac{2N/\left(\frac{E_b}{I_0} \right)_{req}}{\sum\limits_{j=1}^{L-1} E\left[\frac{\nu_{jk}}{\nu_{0k}} \right] + 2} - 1, \quad (8)$$

which is equivalent to

$$K \leq \min_{(x_k, y_k)} \left\{ \frac{2N/\left(\frac{E_b}{I_0} \right)_{req}}{\sum\limits_{j=1}^{L-1} E\left[\frac{\nu_{jk}}{\nu_{0k}} \right] + 2} - 1 \right\}, \quad (9)$$

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

Finally the forward-link capacity in terms of the minimal number of users per cell in CDMA systems without diversity can be obtained from (9), namely

$$C_b = \min_{(x_k, y_k)} \left\{ \frac{2N/\left(\frac{E_b}{I_0} \right)_{req}}{\sum\limits_{j=1}^{L-1} E\left[\frac{\nu_{jk}}{\nu_{0k}} \right] + 2} - 1 \right\} \quad (10)$$

3. CDMA Forward-Link Capacity with Macrodiversity

Now consider the effect of macrodiversity on the forward-link capacity on the basis of the basic model. Suppose that every mobile receives signals from adjacent H BS's ($H \geq 2$) wherever it is in the system. The power of the pilot channel remains P, which is equal to the total allocated power of each mobile. However, because each signal from the involved BS's to the 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 ith BS is $\varpi_{ik} \cdot P$, where ϖ_{ik} represents the weight, and we have $\forall k, \sum\limits_{i=0}^{H-1} \varpi_{ik} = 1$. (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 ϖ_{0k}. The BS that offers the second least signal attenuation to mobile k is number 1 with the weight ϖ_{1k}, 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.

3.1 In Traditional Transmission Scheme

Consider a traditional CDMA system, in which each involved BS transmits the signal to a certain mobile independently with its own code and pilot. Thus H-matched filters are necessary at the mobile receiver in order to detect the H signals from its H BS's. The outputs of the H-matched filters are cophased and combined through the maximal ratio combiner. Details of the mobile receiver block diagram are provided in [2].

Suppose mobile k receives signals from BS 0, 1, $\cdots$, $H-1$. Then its combined $(E_b/I_0)_k$ at the receiver is $\left(\frac{E_b}{I_0} \right)_k = \sum\limits_{i=0}^{H-1} \left(\frac{E_b}{I_0} \right)_{ik}$ [8], where $\left(\frac{E_b}{I_0} \right)_{ik}$ is the bit energy-to-interference PSD ratio of the received signal from the ith BS.

Similar to the analysis in Sect. 2, the signal power at the output of the ith matched filter is $S_{ik} = \nu_{ik} \cdot \varpi_{ik}P$. The interference power at the output of the ith matched filter is

$$I_{ik} = \frac{1}{2N} \sum\limits_{\substack{j=0 \\ j \neq i}}^{L-1} \nu_{jk} \left(\sum\limits_{m=0}^{K_j-1} p_{jm} + P \right)$$

$$+ \frac{1}{N} \cdot \nu_{ik} \cdot \left(\sum\limits_{m=0}^{K_i-2} p_{im} + P \right),$$

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, $j = 0, 1, \cdots, L-1$, and P is the power of the pilot channel.

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

$$\left(\frac{E_b}{I_0} \right)_k = \sum\limits_{i=0}^{H-1} \left(\frac{E_b}{I_0} \right)_{ik}$$

$$= \sum_{i=0}^{H-1} \frac{\nu_{ik} \cdot \varpi_{ik} P}{\frac{1}{2N} \sum_{\substack{j=0 \\ j \neq i}}^{L-1} \nu_{jk} \left(\sum_{m=0}^{K_j-1} p_{jm} + P \right)} \qquad (11)$$
$$+ \frac{1}{N} \cdot \nu_{ik} \cdot \left(\sum_{m=0}^{K_i-2} p_{im} + P \right)$$

For a large number of users, the random variable K_j can be approximated by a Possion random variable with the mean KH. It is proved in Appendix A that

$$\lim_{K \to \infty} \frac{\sqrt{D \left[\sum_{m=0}^{K_j-1} p_{jm} \right]}}{E \left[\sum_{m=0}^{K_j-1} p_{jm} \right]} = 0,$$

$$\lim_{K \to \infty} \frac{\sqrt{D \left[\sum_{m=0}^{K_i-2} p_{im} \right]}}{E \left[\sum_{m=0}^{K_i-2} p_{im} \right]} = 0,$$

where $D[X]$ denotes the variance of the random variable X.

It shows that for a large number of users, the fluctuation around the mean of the interference generated by each involved BS can be neglected. Therefore, the total interference of the jth BS $\sum_{m=0}^{K_j-1} p_{jm}$ and the interference of the ith BS $\sum_{m=0}^{K_i-2} p_{im}$ can be replaced by the mean

$$E \left[\sum_{m=0}^{K_j-1} p_{jm} \right] = \frac{P}{H} \cdot KH \qquad (12)$$

and

$$E \left[\sum_{m=0}^{K_i-2} p_{im} \right] = \frac{P}{H} \cdot (KH - 1) \qquad (13)$$

approximately.

Substituting (12) and (13) into (11) yields

$$\left(\frac{E_b}{I_0} \right)_k = \sum_{i=0}^{H-1} \frac{\nu_{ik} \cdot \varpi_{ik} P}{\frac{1}{2N} \sum_{\substack{j=0 \\ j \neq i}}^{L-1} \nu_{jk} \cdot (KP + P)}$$
$$+ \frac{1}{N} \cdot \nu_{ik} \cdot \left(KP + \frac{H-1}{H} P \right)$$

$$\geq \sum_{i=0}^{H-1} \frac{\nu_{ik} \cdot \varpi_{ik} \cdot 2N}{(K+1) \cdot \left(\sum_{\substack{j=0 \\ j \neq i}}^{L-1} \nu_{jk} + 2 \cdot \nu_{ik} \right)} \qquad (14)$$

According to Jensen's inequality, we have

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

Thus the sufficient condition of the required performance is given by

$$\forall k, \quad \sum_{i=0}^{H-1} \frac{2N}{(K+1) \cdot E \left[\sum_{\substack{j=0 \\ j \neq i}}^{L-1} \frac{\nu_{jk}}{\nu_{ik}} \cdot \frac{1}{\varpi_{ik}} + 2 \cdot \frac{1}{\varpi_{ik}} \right]}$$
$$\geq \left(\frac{E_b}{I_0} \right)_{req} \qquad (15)$$

that is,

$$K \leq \min_{(x_k, y_k)} \left\{ \sum_{i=0}^{H-1} \frac{2N / \left(\frac{E_b}{I_0} \right)_{req}}{E \left[\sum_{\substack{j=0 \\ j \neq i}}^{L-1} \frac{\nu_{jk}}{\nu_{ik}} \cdot \frac{1}{\varpi_{ik}} + 2 \cdot \frac{1}{\varpi_{ik}} \right]} - 1 \right\} \qquad (16)$$

From (16), it is shown that here the forward-link capacity depends on specific power allocation scheme. Once the power allocation scheme is specified, the weight vector $\mathbf{v_k}$ of any mobile k is determined ($\mathbf{v_k} = (\varpi_{0k}, \varpi_{1k}, \cdots, \varpi_{H-1,k})$, $k = 0, 1, \cdots, K-1$). Then substitute ϖ_{ik} into (16), the forward-link capacity with macrodiversity in traditional transmission scheme can be obtained. Therefore, we aim to find the best power allocation scheme in which the maximum forward-link capacity can be achieved.

Suppose

$$g(\mathbf{v_k}) = \sum_{i=0}^{H-1} \frac{\varpi_{ik}}{\sum_{\substack{j=0 \\ j \neq i}}^{L-1} \left[\frac{\nu_{jk}}{\nu_{ik}} \right] + 2}.$$

For any mobile k in the system, we can adjust its weight vector $\mathbf{v_k}$ to $\mathbf{v_k^*}$, in order that $g(\mathbf{v_k^*}) = \max_{\mathbf{v_k}} g(\mathbf{v_k})$. According to (14), such a scheme $\{\mathbf{v_k^*}\}$ 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 is shown in Appendix B that, $\forall k$, when $\mathbf{v_k} = \mathbf{v_k^*} = (1, 0, \cdots, 0)$, $g(\mathbf{v_k^*}) = \max_{\mathbf{v_k}} g(\mathbf{v_k})$, and the corresponding forward-link capacity is

$$C = \min_{(x_k, y_k)} \left\{ \frac{2N / \left(\frac{E_b}{I_0} \right)_{req}}{\sum_{j=1}^{L-1} E \left[\frac{\nu_{jk}}{\nu_{0k}} \right] + 2} - 1 \right\}$$
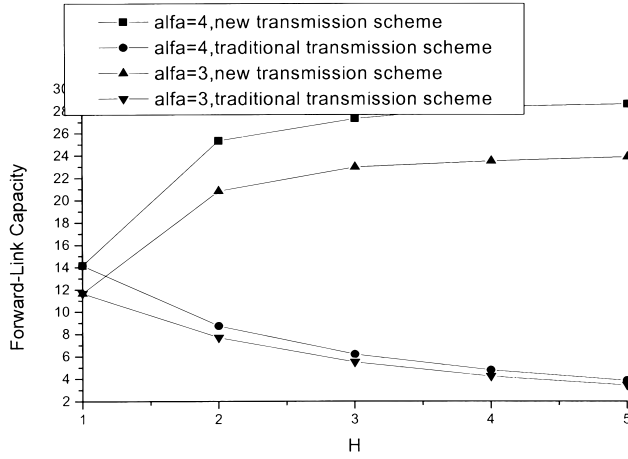
Fig. 1 Forward-link capacity with macrodiversity in the traditional and new transmission scheme.

which is equal to the basic formula of forward-link capacity without macrodiversity (10).

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.

In order to further confirm this conclusion, we take the example of equal power allocation scheme. For any mobile k in the system, suppose $\forall i = 0, 1, \cdots, H-1$, $\varpi_{ik} = 1/H$. Then the forward-link capacity with H BS's macrodiversity can be evaluated by

$$C_e = \min_{(x_k, y_k)} \left\{ \sum_{i=0}^{H-1} \frac{2N / \left(\frac{E_b}{I_0} \right)_{req}}{\sum_{\substack{j=0 \\ j \neq i}}^{L-1} E \left[\frac{\nu_{jk}}{\nu_{ik}} \right] + 2} \cdot \frac{1}{H} - 1 \right\} \quad (17)$$

This expression gives the forward-link capacity as a function of the number of involved BS's H. The simulation results are shown in Fig. 1 and discussed in Sect. 5.

3.2 In New Transmission Scheme

From the derivation above, it can be seen that 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 transmission signal power among several BS's will cause a decrease of the received signal power compared with the case without macrodiversity. That's why macrodiversity always leads to capacity loss in the traditional

transmission scheme whatever power allocation scheme is adopted.

Based on this analysis, we present a new transmission scheme. In this scheme, all BS's involved transmit the same information to a certain mobile 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.

Assume that mobile k communicates with BS 0, 1, $\cdots$, $H-1$. The signal transmitted from each involved BS to mobile k is exactly the same, and these signals are jointly adjusted in order to arrive in phase and simultaneously.

Then the signal power at the output of the matched filter is

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

$$= P \cdot \left(\sum_{i=0}^{H-1} \sqrt{\nu_{ik} \cdot \varpi_{ik}} \right)^2 \quad (18)$$

The interference power at the output of the matched filter is

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

$$+ \frac{1}{2N} \sum_{j=0}^{H-1} \nu_{jk} \left(\sum_{m=0}^{K_j-2} p_{jm} + P \right) \quad (19)$$

From (18) and (19), we have

$$\left(\frac{E_b}{I_0} \right)_k = \frac{P \cdot \left(\sum\limits_{i=0}^{H-1} \sqrt{\nu_{ik} \cdot \varpi_{ik}} \right)^2}{\frac{1}{2N} \sum\limits_{j=H}^{L-1} \nu_{jk} \left(\sum\limits_{m=0}^{K_j-1} p_{jm} + P \right) + \frac{1}{2N} \sum\limits_{j=0}^{H-1} \nu_{jk} \left(\sum\limits_{m=0}^{K_j-2} p_{jm} + P \right)}$$

$$= \frac{P \cdot \left(\sum\limits_{i=0}^{H-1} \sqrt{\nu_{ik} \cdot \varpi_{ik}} \right)^2}{\frac{1}{2N} \sum\limits_{j=H}^{L-1} \nu_{jk} \left(KP + P \right) + \frac{1}{2N} \sum\limits_{j=0}^{H-1} \nu_{jk} \left(KP + \frac{H-1}{H} P \right)}$$

$$\geq \frac{2N \cdot \left(\sum\limits_{i=0}^{H-1} \sqrt{\nu_{ik} \cdot \varpi_{ik}}\right)^2}{(K+1) \cdot \sum\limits_{j=0}^{L-1} \nu_{jk}} \qquad (20)$$

Similarly, in order to maximize the forward-link capacity, suppose that $g\left(\mathbf{v_k}\right) = \sum\limits_{i=0}^{H-1} \sqrt{\nu_{ik}\varpi_{ik}}$. Then from (20) it is obvious that such a scheme $\{\mathbf{v_k^*}\}$ that satisfies $g\left(\mathbf{v_k^*}\right) = \max\limits_{\mathbf{v_k}} g\left(\mathbf{v_k}\right)$ is the best one in which the maximum forward-link capacity can be achieved.

It is proved in Appendix C that, for $\forall k$, when

$$\mathbf{v_k} = \mathbf{v_k^*} = \left(\frac{\nu_{0k}}{\sum\limits_{i=0}^{H-1} \nu_{ik}}, \ \frac{\nu_{1k}}{\sum\limits_{i=0}^{H-1} \nu_{ik}}, \ \cdots \ \frac{\nu_{H-1,k}}{\sum\limits_{i=0}^{H-1} \nu_{ik}}\right),$$

$$g(\mathbf{v_k^*}) = \max_{\mathbf{v_k}} g\left(\mathbf{v_k}\right) = \sqrt{\sum\limits_{i=0}^{H-1} \nu_{ik}} \qquad (21)$$

Substituting (21) into (20) yields:

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

According to Jensen's inequality, we have

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

Then the forward-link capacity with macrodiversity in the new transmission scheme can be derived to be:

$$C_a = \min_{(x_k,y_k)} \left\{\sum\limits_{i=0}^{H-1} \frac{2N/\left(\frac{E_b}{I_0}\right)_{req}}{\sum\limits_{\substack{j=0 \\ j\neq i}}^{L-1} E\left[\frac{\nu_{jk}}{\nu_{ik}}\right] + 1} - 1\right\} \qquad (22)$$

From (22), it can be foreseen that in this new scheme the forward-link capacity will increase with H. The simulation results are shown in Fig. 1 and discussed in Sect. 5.

4. CDMA Forward-Link Capacity with Microdiversity

Now consider the effect of microdiversity on the forward-link capacity. We assume that each BS uses a multi-element antenna array to transmit signals to mobiles. Let H be the number of antenna elements. It is well known that with an antenna array, the BS must also beamform on the forward link in order to effectively increase the system capacity. Thus suppose that transmission beamforming can be performed in every BS, that is, the signals received from the antenna elements in the same BS are cophased at the mobile. The power of the pilot channel remains 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 from each antenna element to a certain mobile is the same, namely, P/H.

On these assumptions, for a mobile k located in the zeroth cell, the signal power at the output of the matched filter is $S_k = \left(H \cdot \sqrt{\nu_{0k} \cdot P/H}\right)^2 = PH \cdot \nu_{0k}$. The interference power at the output of the matched filter is

$$I_k = \frac{1}{2N} \cdot \sum\limits_{j=1}^{L-1} \nu_{jk} \cdot H \cdot \left(K \cdot \frac{P}{H} + P\right)$$
$$+ \frac{1}{2N} \cdot \nu_{0k} \cdot H \cdot \left[(K-1) \cdot \frac{P}{H} + P\right] \qquad (23)$$

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

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

According to Jensen's inequality, we have

$$E\left[\left(\frac{E_b}{I_0}\right)_k\right]$$
$$\geq \frac{PH}{\begin{array}{c}\frac{1}{2N} \sum\limits_{j=1}^{L-1} E\left[\frac{\nu_{jk}}{\nu_{0k}}\right] \cdot H\left(\frac{K}{H} + 1\right)P \\ + \frac{1}{2N}H\left(\frac{K-1}{H} + 1\right)P\end{array}}$$
$$\geq \frac{2N}{\left(\frac{K}{H} + 1\right)\left(\sum\limits_{j=1}^{L-1} E\left[\frac{\nu_{jk}}{\nu_{0k}}\right] + 1\right)}$$

Thus a sufficient condition of the required performance is given by

$$K \leq \min_{(x_k,y_k)} \left\{\left[\frac{2N/\left(\frac{E_b}{I_0}\right)_{req}}{\sum\limits_{j=1}^{L-1} E\left[\frac{\nu_{jk}}{\nu_{0k}}\right] + 1} - 1\right] \cdot H\right\} \qquad (24)$$

and the forward-link capacity with the antenna array of H elements can be evaluated by

$$C_i = \min_{(x_k,y_k)} \left\{ \left[\frac{2N/\left(\frac{E_b}{I_0}\right)_{req}}{\sum_{j=1}^{L-1} E\left[\frac{\nu_{jk}}{\nu_{0k}}\right] + 1} - 1 \right] \cdot H \right\} \quad (25)$$

It's clear that the capacity increases in proportion to H.

However, it should be pointed out that here the total number of antennas is H times that with macrodiversity. In order to make a fair comparison between the forward-link capacity with macrodiversity and that with microdiversity, we consider a scenario that the region area remains the same but is divided into LH cells. Every mobile receives signals from adjacent H BS's ($H \geq 2$) and no antenna array is used in each BS. Then from the derivation in the previous section, the forward-link capacity with H BS's macrodiversity in the new transmission scheme can be evaluated by

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

Besides, now the cell area has been reduced to $1/H$ of the original area. Thus in order to be consistent with the forward-link capacity with microdiversity, the capacity with H BS's macrodiversity should be

$$C_a = \min_{(x_k,y_k)} \left\{ \left[\sum_{i=0}^{H-1} \frac{2N/\left(\frac{E_b}{I_0}\right)_{req}}{\sum_{\substack{j=0 \\ j\neq i}}^{LH-1} E\left[\frac{\nu_{jk}}{\nu_{ik}}\right] + 1} - 1 \right] \cdot H \right\} \quad (26)$$

The simulation results are shown in Fig. 2 and discussed in Sect. 5.
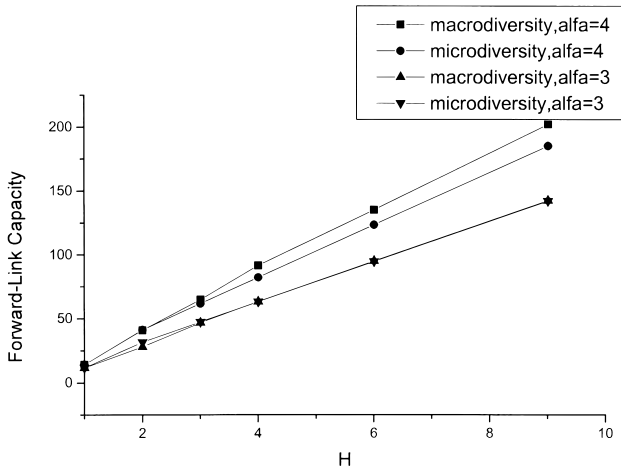
Fig. 2 Forward-link capacity with microdiversity and macrodiversity.

5. Simulation Results and Discussions

We consider only the first two tiers of interfering cells, which means $L=19$. We assume that for adequate performance, the required BER is 10^{-3} that corresponds to the required average bit energy-to-interference PSD ratio $(E_b/I_0)_{req} = 7$ dB. We also assume that the spreading factor $N=127$ and $\sigma = 8$ dB.

With macrodiversity the forward-link capacity for different values of the number of involved BS's H in the traditional and new transmission schemes can be calculated using (17) and (22), respectively. The results are summarized in Fig. 1 for the path-loss exponent α of 4 and 3. From Fig. 1, it is shown that in the traditional transmission scheme, the forward-link capacity decreases rapidly with the number of involved BS's H if the equal power allocation scheme is adopted. However, in the new transmission scheme, the capacity increases with H and thus much higher capacity can be obtained in the best power allocation scheme. The comparison of the simulation results in these two transmission schemes reveals clearly that in the new transmission scheme macrodiversity brings substantial capacity benefits instead of loss and the benefits increase with H. However, in spite of the capacity benefits, the system complexity also rises greatly since in the new scheme, for every mobile a joint control is required among all the involved BS's that are widely separated.

In fact, the principle of the new transmission scheme is similar to that of beamforming. As we mentioned before, with an antenna array, the BS must also beamform to effectively increase the system capacity. Similarly, with macrodiversity, the signals from the involved BS's must also be adjusted jointly to arrive at the mobile in phase and simultaneously. Otherwise macrodiversity will cause capacity loss. Thus we further make a comparison of the forward-link capacity with microdiversity and that with macrodiversity in the new transmission scheme. The simulation results are summarized in Fig. 2 for the path-loss exponent α of 4 and 3. From Fig. 2, it is shown that when α is 4, the forward-link capacity increases rapidly with H in both types of diversity. However, as H increases the forward-link capacity with macrodiversity grows faster. In order to analyze the fact, we define the interference antennas in the first tier as those interference antennas at the same distance from the desired mobile as the useful antennas. Then from (25) and (26), it can be seen that the capacity depends on the relative interference level, which can be approximately estimated by the number of interference antennas in the first tier in the worst case. The relative interference becomes stronger with more interference antennas in the first tier and thus the forward-link capacity gets lower. It is obvious that in the worst case the number of interference antennas in the first tier is one at most with H BS's macrodiversity
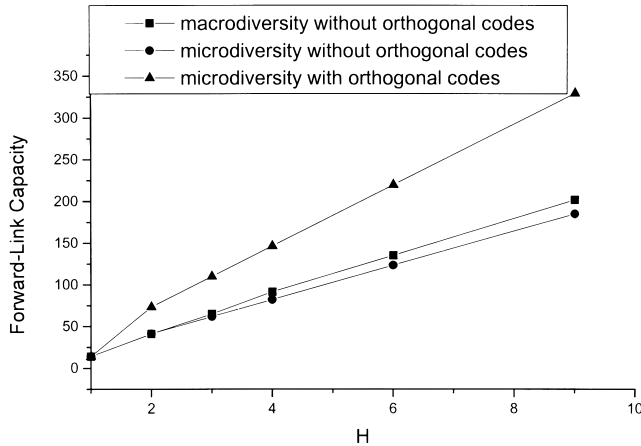
Fig. 3 Forward-link capacity with orthogonal codes in microdiversity and without orthogonal codes in microdiversity and macrodiversity when $\alpha=4$.

and $2H$ with H antennas microdiversity, respectively. Therefore with macrodiversity higher forward-link capacity can be obtained in comparison with microdiversity and the capacity gap becomes wider with the increase of H. Nevertheless, with macrodiversity the system complexity is also higher since the adjustment of signal timing and phase is more difficult.

Moreover, from (25) and (26), 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 simulations. From Fig. 2, it is shown that though in both types of diversity the forward-link capacity falls off when α is reduced to 3, the capacity loss with macrodiversity is greater.

It should be pointed out that with H antennas microdiversity, if orthogonal codes are used, interference will be primarily due to the outside cell interference (the second term on the right of (23) becomes zero) and thus the forward-link capacity will be increased greatly. However, with H BS's macrodiversity, since different mobiles communicate with different BS's, it is difficult to allocate orthogonal codes among the mobiles. Thus capacity enhancement cannot be obtained through this approach with macrodiversity. In Fig. 3, we plot the forward-link capacity with orthogonal codes in microdiversity and the forward-link capacity without orthogonal codes in microdiversity and macrodiversity ($\alpha =4$).

6. Conclusions

We have studied the effects of macrodiversity and microdiversity on the forward-link capacity in CDMA systems by using an average bit energy-to-interference PSD ratio corresponding to a BER of 10^{-3}. We prove that in traditional transmission scheme, the maximum

forward-link capacity can be achieved without macrodiversity. This also means that in this case macrodiversity always causes forward-link capacity loss. After analyzing the cause of capacity loss, we present a new transmission scheme in which the capacity increases rapidly with the number of involved BS's H if the transmission power allocated to a certain mobile from each involved BS is proportional to the channel gain between them. The comparison of the forward-link capacity with microdiversity and that with macrodiversity in the new scheme shows that both types of diversity bring benefits to the forward-link capacity. With macrodiversity the capacity goes up faster with H but is more sensitive to the path-loss exponent α. When α is reduced from 4 to 3, the advantages disappear rapidly.

In spite of more capacity enhancement gained with macrodiversity in the new transmission scheme, the system complexity is also higher. With microdiversity, signals from the same BS arrived at the mobile in phase and simultaneously since they propagate through the same path. However, with macrodiversity a more complex adjustment of signal phase and 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.

Our model does not include the effect of multipath that will be investigated later. Moreover, since we are concerned about the percentage of capacity change, in this paper we used average bit energy-to-interference PSD ratio to evaluate the capacity. Our future research will be based on a more precise model in which outage probability is used.

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Appendix A

$$\lim_{K\to\infty} \frac{\sqrt{D\left[\sum_{m=0}^{K_j-1} p_{jm}\right]}}{E\left[\sum_{m=0}^{K_j-1} p_{jm}\right]} = 0, \ \lim_{K\to\infty} \frac{\sqrt{D\left[\sum_{m=0}^{K_i-2} p_{im}\right]}}{E\left[\sum_{m=0}^{K_i-2} p_{im}\right]} = 0$$

Proof: In [9], it is proved that, suppose $X = \sum_{n=1}^{N} Y_n$, N is a Possion random variable, and $\{Y_n\}$ is a group of i.i.d. discrete random variables, then $E[X] = E[N] \cdot E[Y]$, $D[X] = E[N] \cdot E[Y^2]$.

Since all mobiles are uniformly distributed in each cell, we have $\forall j$, $E[K_j] = KH$, $\Pr\{p_{jm} = \varpi_{im} \cdot P\} = 1/H$, where the subscript i of ϖ_{im} represents the number of the jth BS for mobile m, $i = 0, 1, \cdots, H-1$.

Therefore,

$$E[p_{jm}] = \sum_{i=0}^{H-1} \varpi_{im} P \cdot \Pr\{p_{jm} = \varpi_{im} P\}$$
$$= \frac{P}{H} \cdot \sum_{i=0}^{H-1} \varpi_{im} = P/H.$$

Here $\{p_{jm}\}$ is a group of i.i.d. discrete random variables, and K_j has a Possion distribution. Thus

$$E\left[\sum_{m=0}^{K_j-1} p_{jm}\right] = E[K_j] \cdot E[p_{jm}] = KH \cdot \frac{P}{H}$$

$$D\left[\sum_{m=0}^{K_j-1} p_{jm}\right] = E[K_j] \cdot E\left[(p_{jm})^2\right] = KH \cdot \mu$$

It can be derived that

$$\mu = E\left[(p_{jm})^2\right]$$
$$= \sum_{i=0}^{H-1} (\varpi_{im} P)^2 \cdot \Pr\{p_{jm} = \varpi_{im} P\}$$

$$= \frac{P^2}{H} \sum_{i=0}^{H-1} \varpi_{im}^2 < P^2.$$

Therefore

$$\lim_{K\to\infty} \frac{\sqrt{D\left[\sum_{m=0}^{K_j-1} p_{jm}\right]}}{E\left[\sum_{m=0}^{K_j-1} p_{jm}\right]} = \lim_{K\to\infty} \frac{\sqrt{KH \cdot \mu}}{KH \cdot \frac{P}{H}} = 0.$$

Similarly, we have

$$E\left[\sum_{m=0}^{K_i-2} p_{im}\right] = (KH-1) \cdot \frac{P}{H},$$

$$\lim_{K\to\infty} \frac{\sqrt{D\left[\sum_{m=0}^{K_i-2} p_{im}\right]}}{E\left[\sum_{m=0}^{K_i-2} p_{im}\right]} = \lim_{K\to\infty} \frac{\sqrt{(KH-1) \cdot \mu}}{(KH-1) \cdot \frac{P}{H}}$$
$$= 0.$$

Appendix B

$\forall k$, when $\mathbf{v_k} = \mathbf{v_k^*} = (1, \ 0, \ \cdots \ 0)$,

$$g(\mathbf{v_k^*}) = \max_{\mathbf{v_k}} g(\mathbf{v_k})$$

$$= \max_{\mathbf{v_k}} \left(\sum_{i=0}^{H-1} \frac{\varpi_{ik}}{\sum_{\substack{j=0 \\ j\neq i}}^{L-1} \left[\frac{\nu_{jk}}{\nu_{ik}}\right] + 2} \right)$$

Proof: Suppose $f(\mathbf{v}) = \sum_{i=0}^{H-1} a_i \varpi_i$, where the coefficients $\{a_i\}$ satisfy: $\forall i, a_i \geq 0$, and $a_0 \geq a_1 \geq \cdots \geq a_{H-1}$, and $\mathbf{v}$ satisfies $\sum_{i=0}^{H-1} \varpi_i = 1$, then

$$f(\mathbf{v}) = \sum_{i=0}^{H-1} a_i \varpi_i \leq a_0 \sum_{i=0}^{H-1} \varpi_i = a_0$$
$$= a_0 \cdot 1 + a_1 \cdot 0 + \cdots + a_{H-1} \cdot 0.$$

Therefore, when $\mathbf{v} = \mathbf{v^*} = (1, 0, \cdots, 0)$, $f(\mathbf{v^*}) = \max f(\mathbf{v})$.

About $g(\mathbf{v_k})$, suppose

$$a_{ik} = \frac{1}{\sum_{\substack{j=0 \\ j\neq i}}^{L-1} \left[\frac{\nu_{jk}}{\nu_{ik}}\right] + 2},$$

then

$$g(\mathbf{v_k}) = \sum_{i=0}^{H-1} a_{ik} \cdot \varpi_{ik}.$$

It is known that $\forall k, \nu_{0k} \geq \nu_{1k} \geq \cdots \geq \nu_{H-1,k}$. Thus

$$\forall i \neq 0, \sum_{\substack{j=0 \\ j \neq i}}^{L-1} \frac{\nu_{jk}}{\nu_{ik}} \geq \sum_{\substack{j=0 \\ j \neq i}}^{L-1} \frac{\nu_{jk}}{\nu_{0k}} \geq \sum_{j=1}^{L-1} \frac{\nu_{jk}}{\nu_{0k}},$$

that is, $\forall k, a_{0k} \geq a_{ik}, \; i = 1, \; \cdots, \; H-1$.

Therefore, $\forall k$, when $\mathbf{v_k} = \mathbf{v_k^*} = (1, 0, \cdots, 0)$, $g(\mathbf{v_k^*}) = \max_{\mathbf{v_k}} g(\mathbf{v_k})$.

Appendix C

$\forall k$, when

$$\mathbf{v_k} = \mathbf{v_k^*} = \left(\frac{\nu_{0k}}{\sum\limits_{i=0}^{H-1} \nu_{ik}}, \; \frac{\nu_{1k}}{\sum\limits_{i=0}^{H-1} \nu_{ik}}, \; \cdots \frac{\nu_{H-1,k}}{\sum\limits_{i=0}^{H-1} \nu_{ik}} \right),$$

$$g(\mathbf{v_k^*}) = \max_{\mathbf{v_k}} g(\mathbf{v_k}) = \max_{\mathbf{v_k}} \left(\sum_{i=0}^{H-1} \sqrt{\nu_{ik} \varpi_{ik}} \right).$$

Proof: $\forall k$, suppose

$$f(\mathbf{v_k}) = \sum_{i=0}^{H-1} \sqrt{\nu_{ik} \varpi_{ik}} - \lambda \left(\sum_{i=0}^{H-1} \varpi_{ik} - 1 \right),$$

then from $\frac{\partial f(\mathbf{v_k})}{\partial \varpi_{ik}} = \sqrt{\nu_{ik}} \cdot \frac{1}{2\sqrt{\varpi_{ik}}} - \lambda = 0$, we have

$$\begin{cases} \dfrac{\varpi_{0k}^*}{\nu_{0k}} = \dfrac{\varpi_{1k}^*}{\nu_{1k}} = \cdots = \dfrac{\varpi_{H-1,k}^*}{\nu_{H-1,k}} \\ \sum\limits_{i=0}^{H-1} \varpi_{ik}^* = 1 \end{cases}.$$

Thus it can be derived that $\forall k$,

$$\mathbf{v_k^*} = \left(\frac{\nu_{0k}}{\sum\limits_{i=0}^{H-1} \nu_{ik}}, \; \frac{\nu_{1k}}{\sum\limits_{i=0}^{H-1} \nu_{ik}}, \; \cdots \frac{\nu_{H-1,k}}{\sum\limits_{i=0}^{H-1} \nu_{ik}} \right),$$

and

$$g(\mathbf{v_k^*}) = \max_{\mathbf{v_k}} g(\mathbf{v_k}) = \sum_{i=0}^{H-1} \sqrt{\nu_{ik} \varpi_{ik}^*}$$

$$= \sqrt{\sum_{i=0}^{H-1} \nu_{ik}}.$$

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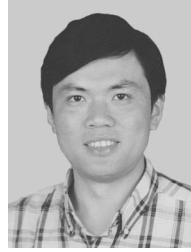
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