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Frequency-Domain Equalization for MC-CDMA Downlink Site Diversity and Performance Evaluation

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SUMMARY Similar to direct sequence code division multiple access (DS-CDMA), site diversity can be applied to a multicarrier-CDMA (MC-CDMA) cellular system to improve the bit error rate (BER) performance for a user with weak received signal power, thus resulting in an increased link capacity. In this paper, the downlink site diversity reception using frequency-domain equalization based on minimum mean square error (MMSE) is considered for a MC-CDMA cellular system. A set of active base stations to be involved in the site diversity operation is determined based on the received signal power measurement by a mobile station. Downlink capacity with site diversity is evaluated by computer simulation. The impacts of path loss exponent and shadowing loss standard deviation on the site diversity effect are discussed. Furthermore, the performance improvement by antenna diversity reception is discussed.

key words: MC-CDMA, site diversity, MMSE frequency-domain equalization

1. Introduction

The broadband mobile radio channels are characterized by frequency-selective fading, which significantly degrades the transmission performance [1]. For high-speed data transmission in such a frequency-selective fading channel, multicarrier code division multiple access (MC-CDMA) has been intensively studied and is considered as the most promising candidate for the next generation mobile communications systems [2]–[5]. In a MC-CDMA cellular system, the same carrier frequency can be reused in the all base stations (BS's) similar to a direct sequence CDMA (DS-CDMA) cellular system [6]. The single-cell frequency reuse allows the introduction of site diversity to improve the transmission performance for a user with weak received signal power, thus resulting in an increased link capacity.

In this paper, we consider the downlink site diversity reception in a MC-CDMA cellular system. For site diversity, a set of active BS's is selected based on the received signal power measurement by a mobile station (MS). For selection of active BS's, the threshold P_{th} is introduced. A BS giving the local average received power within the threshold P_{th} from the maximum is selected as an active BS. It is well-known [7]–[9] that frequency-domain equalization (FDE) based on minimum mean square error (MMSE) criterion provides a good bit error rate (BER) performance. In this paper, site diversity combining using MMSE-FDE is considered. However, if the MMSE weight designed for the

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single cell environment is applied to the site diversity combining, the BER performance significantly degrades. This is because the inter-cell interference (ICI) cannot be ignored under a multi-cell environment. Therefore, in this paper, we derive the MMSE-FDE weight for the site diversity combining taking into account both the ICI and noise. Also in this paper, the antenna diversity reception combined with site diversity is considered for further improvement in the link capacity.

The objective of this paper is to derive the MMSE-FDE weight for site diversity combining, to find the optimum threshold that maximizes the downlink capacity, to find the required maximum number of active BS's, and to show how the joint use of site diversity and antenna diversity combining is advantageous as in DS-CDMA system. Also discussed in this paper is the effect of propagation parameters on the link capacity. The remainder of this paper is organized as follows. The downlink site diversity system model is presented and MMSE-FDE weight for the downlink site diversity combining is derived in Sect. 2. In Sect. 3, simulation results are presented and discussed. Section 4 concludes this paper.

2. MC-CDMA Downlink Site Diversity

2.1 Overall System Model

The mobile channel is characterized by the distance dependent path loss, shadowing loss, and multipath frequency selective fading. For selection of active BS's for site diversity operation, we introduce a threshold P_{th} . Before starting communication, each MS measures the local average received signal power of its surrounding BS's and then, sorts out the BS's in descending order based on the local average received power. "Local average" means taking the average of the instantaneous received signal power so that the instantaneous variation in the received signal power due to fading is smoothed out but the effects of distance dependent path loss and shadowing loss are kept intact. The local average received power can be estimated using pilot symbols periodically transmitted from each BS. However, in this paper, we assume ideal power estimation. Each MS selects BS's having the local average received powers within the threshold P_{th} from the maximum as active BS's (hence, the number of active BS's can be controlled by the threshold) and report this to the radio network controller (RNC) via uplink. The RNC sends the same data sequence of a user of interest to

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all the active BS's for the downlink site diversity transmission. The active BS's spread, in the frequency-domain, and transmit simultaneously the same data sequence sent from the RNC. For users without site diversity, $P_{th}=0$ is used. Figure 1 shows site diversity model for the case of 3 active BS's.

When the threshold is too small, the number of active BS's becomes small and hence the link capacity decreases. On the other hand, when the threshold is too high, the number of active BS's becomes large and hence the interference power increases, resulting in the reduced link capacity.



Fig. 1 Site diversity model.

Therefore, an optimum site diversity threshold may exist. The threshold and the maximum number of active BS's for site diversity are important design parameters.

2.2 MC-CDMA Downlink Signal Transmission

Figure 2 shows the MC-CDMA transmitter/receiver structure for site diversity. An MC-CDMA with N_c subcarriers and spreading factor *SF* is assumed. In this paper, it is assumed that N_c is equal to the number of fast Fourier transform (FFT) points. At the *i*th BS, a sequence of datamodulated symbols $\{x_{u(i)}(n); n = 0 \sim N_c/SF - 1\}$ of the *u*th user u(i) in the *i*th cell is to be transmitted during one MC-CDMA signaling period. After serial-to-parallel (S/P) conversion, each symbol in the sequence is copied *SF* times and multiplied by an OVSF code $\{c_{u(i)}(k); k = 0 \sim SF - 1\}$ [10]. All users' subcarrier components are combined and multiplied by a BS-specific common scrambling code $\{c_{scr,i}(k); k = 0 \sim N_c - 1\}$. The scrambling code is used for making the transmit signal noise like and for separating the BS. We assume $|x_{u(i)}(n)| = |c_{u(i)}(k)| = |c_{scr,i}(k)| = 1$.

In this paper, the T_c -spaced discrete time representation of the signal is used, where T_c is the sampling period for inverse FFT (IFFT). The *i*th BS's *k*th subcarrier component



Fig. 2 MC-CDMA transmitter/receiver structure for site diversity.

 $s_i(k)$ can be expressed in the equivalent lowpass representation as

$$s_i(k) = \sqrt{\frac{2P_i}{SF}} \sum_{u(i)=0}^{U_i-1} c_{u(i)}(k \mod SF) c_{scr_i}(k) x_{u(i)}\left(\left\lfloor \frac{k}{SF} \right\rfloor\right),$$
(1)

where P_i is the transmit signal power per user and U_i is the number of active channels in the *i*th BS. N_c -point IFFT is applied to generate the MC-CDMA signal. MC-CDMA signal $s_i(t)$ after insertion of N_g -sample guard interval (GI) can be expressed as

$$s_i(t) = \sum_{k=0}^{N_c - 1} s_i(k) \exp\left(j2\pi k \frac{t}{N_c}\right) \quad \text{for } t = -N_g \sim N_c - 1.$$
 (2)

We assume a frequency-selective fading channel with *L* independent propagation paths. The path gain and time delay of the *l*th path between the *i*th BS and the *m*th receive antenna of the user u(j) in the *j*th cell are denoted as $\xi_{i_u(j),l}^{(m)}$ and τ_l , respectively, with $E\left[\sum_{l=0}^{L-1} \left|\xi_{i_u(j),l}^{(m)}\right|^2\right] = 1$ (*E*[.] denotes the ensemble average operation). The MC-CDMA signal $r_{u(j)}^{(m)}(t)$ received by the *m*th antenna of user u(j) is given by

$$r_{u(j)}^{(m)}(t) = \sum_{i=0}^{\infty} \sum_{l=0}^{L-1} \xi_{i,u(j),l}^{(m)} s_i(t-\tau_l) + \eta^{(m)}(t)$$

for $t = -N_g \sim N_c - 1$, (3)

where $\eta^{(m)}(t)$ represents the additive white Gaussian noise (AWGN) having zero mean and variance $2N_0/T_c$ with N_0 representing single sided AWGN power spectrum density.

At the receiver of the user u(j), after removal of the GI, N_c -point FFT is applied to decompose the received signal into N_c subcarrier components. The *k*th subcarrier component $R_{u(j)}^{(m)}(k)$ is given by

$$R_{u(j)}^{(m)}(k) = \frac{1}{N_c} \sum_{t=0}^{N_c-1} r_{u(j)}^{(m)}(t) \exp\left(-j2\pi k \frac{t}{N_c}\right) = \sum_{i=0}^{\infty} H_{i \downarrow u(j)}^{(m)}(k) \\ \times \left\{ \sqrt{\frac{2S_{i \downarrow u(j)}}{SF}} \sum_{u(i)=0}^{U_i-1} c_{u(i)}(k \mod SF) c_{scr \downarrow}(k) x_{u(i)} \left(\left\lfloor \frac{k}{SF} \right\rfloor \right) \right\} \\ + \Pi^{(m)}(k), \tag{4}$$

where $S_{i,u(j)}$ represents the local average received power of the signal transmitted from the *i*th BS which is given by

$$S_{i,\mu(j)} = P_i r_{i,\mu(j)}^{-\alpha} 10^{-\beta/10},$$
(5)

where $r_{i,u(j)}$ is the distance between the *i*th BS and the user u(j), α is path loss exponent, and β is the log-normally distributed shadowing loss. $H_{i,u(j)}^{(m)}(k)$ is the channel gain at the *k*th subcarrier for the *m*th receive antenna and is given by

$$H_{i,\mathcal{U}(j)}^{(m)}(k) = \sum_{l=0}^{L-1} \xi_{i,\mathcal{U}(j),l}^{(m)} \exp\left(-j2\pi k \frac{\tau_l}{N_c}\right).$$
 (6)

Each subcarrier component is multiplied by the complex conjugate of scrambling code to extract the desired signal component. MMSE-FDE is carried out using the following weight for the *d*th BS (for the derivation, see Appendix):

$$w_{d \downarrow \iota(j)}^{(m)}(k) = \frac{\Gamma_{d \downarrow \iota(j)} H_{d \downarrow \iota(j)}^{(m)*}(k)}{\sum_{i=0}^{\infty} \Gamma_{i \downarrow \iota(j)} U_i \sum_{m=0}^{M-1} \left| H_{i \downarrow \iota(j)}^{(m)}(k) \right|^2 + SF}$$
(7)

with

$$\Gamma_{i \downarrow \iota(j)} = \frac{S_{i \downarrow \iota(j)} N_c T_c}{N_0} = \Lambda_{i \downarrow \iota(j)} r_{i \downarrow \iota(j)}^{-\alpha} 10^{-\beta/10},$$
(8)

where $\Lambda_{i,u(j)}$ (= $P_iN_cT_c/N_0$) represents the transmit signal energy per symbol-to-the AWGN power spectrum density ratio. All the subcarrier components transmitted from active BS's and received by *M* receive antennas are combined and despreading is carried out to obtain the decision variable $\hat{x}_{u(j)}(n)$ for the *n*th data-modulated symbol:

$$\hat{x}_{u(j)}(n) = \frac{1}{SF} \sum_{k=nSF}^{(n+1)SF-1} \left(\sum_{m=0}^{M-1} \sum_{d=0}^{D-1} \varepsilon_d R_{u(j)}^{(m)}(k) w_{d \downarrow u(j)}^{(m)}(k) c_{scr \lrcorner d}^*(k) \right) \\ \times c_{u(j)}^*(k \bmod SF),$$
(9)

where *D* is the allowable maximum number of active BS's and $\varepsilon_d = 1$ (0) for the BS with $\Delta_d < P_{th}$ (otherwise) with Δ_d being the difference of local average received power for the *d*th BS from the maximum. In the above, we assume that the BS index is given in the descending order of the local average received signal power. If more than *D* BS's satisfy $\Delta_d < P_{th}$, only the *D* strongest BS's are selected for the site diversity operation.

The N_c/SF decision variables $\{\hat{x}_{u(j)}(n)\}\$ are parallel-toserial (P/S) converted and then, data demodulation is done to recover the transmitted binary sequence.

2.3 Equivalent Channel Gain after Equalization

Substituting Eqs. (4) and (7) into Eq. (9), we have

$$\hat{x}_{u(j)}(n) = \left(\frac{1}{SF} \sum_{k=nSF}^{(n+1)SF-1} \tilde{H}_{u(j)}(k)\right) x_{u(j)}(n) + \mu_{ISI}(n) + \mu_{ICI}(n) + \mu_{AWGN}(n),$$
(10)

where $\tilde{H}_{u(j)}(k)$ is the equivalent channel gain at the *k*th subcarrier after site diversity combining, given by

$$\tilde{H}_{u(j)}(k) = \sum_{m=0}^{M-1} \sum_{d=0}^{D-1} \varepsilon_d \sqrt{\frac{2S_{d \perp u(j)}}{SF}} \tilde{H}_{d \perp u(j)}^{(m)}(k)$$
(11)

with

$$\tilde{H}_{d,u(j)}^{(m)}(k) = H_{d,u(j)}^{(m)}(k)w_{d,u(j)}^{(m)}(k).$$
(12)

The first term of Eq. (10) is the desired signal component, the second the inter-symbol interference (ISI) component, the third the ICI component and the fourth the noise component due to the AWGN, and they are given by



Fig. 3 Channel gain and equivalent channel gain after site diversity when $(\Delta_0, \Delta_1, \Delta_2, \Delta_3, \Delta_4, \Delta_5, \Delta_6) = (0, -2, -13, -18, -18, -27, -29) \text{ dB}.$

$$I_{ISI}(n) = \frac{1}{SF} \sum_{k=nSF}^{(n+1)SF-1} \sum_{m=0}^{M-1} \sum_{d=0}^{D-1} \sum_{\substack{u(i)=0\\ \neq u(j)}}^{U_i-1} \varepsilon_d \sqrt{\frac{2S_{d-u(j)}}{SF}} \tilde{H}_{d_{-u(j)}}^{(m)}(k)$$

$$\times c_{u(i)}(k \mod SF) c_{u(j)}^*(k \mod SF) x_{u(i)}(n)$$
(13)

 $\mu_{ICI}(n)$

$$= \frac{1}{SF} \sum_{k=nSF}^{(n+1)SF-1} \sum_{m=0}^{M-1} \sum_{d=0}^{D-1} \sum_{i=0}^{\infty} \sum_{u(i)=0}^{U_i-1} \varepsilon_d \sqrt{\frac{2S_{i_u(j)}}{SF}} H_{i_u(j)}^{(m)}(k) \times w_{d_u(j)}^{(m)}(k) c_{scr_i}(k) c_{scr_d}^*(k) \times c_{u(i)}(k \mod SF) c_{u(i)}^*(k \mod SF) x_{u(i)}(n),$$
(14)

and

$$\mu_{AWGN}(n) = \frac{1}{SF} \sum_{k=nSF}^{(n+1)SF-1} \sum_{m=0}^{M-1} \sum_{d=0}^{D-1} \varepsilon_d w_{d,u(j)}^{(m)}(k)$$
$$\times c^*_{scr,d}(k) c^*_{u(j)}(k \mod SF) \Pi^{(m)}(k).$$
(15)

Fig. 3 shows the channel gain and the equivalent channel gain after site diversity when $\Lambda_{d.u(j)}=30 \text{ dB}$ for all d and D=7. The threshold $P_{th}=4.5 \text{ dB}$ is assumed. The case where the local average received signal powers of the 0th BS and the 1st BS are higher than five other BS's is shown in Fig. 3. The relative received signal powers are $(\Delta_0, \Delta_1, \Delta_2, \Delta_3, \Delta_4, \Delta_5, \Delta_6) = (0, -2, -13, -18, -18, -27, -29) \text{ dB}$. Two strongest BS's (i.e., the 0th BS and 1st BS) are participating in the site diversity operation (i.e., $\varepsilon_0 = \varepsilon_1 = 1$ and $\varepsilon_d = 0$ for $d = 2 \sim 6$). Although variations in the 0th and 1st BS's equivalent channel gains after MMSE-FDE still remain, the equivalent channel gain after site diversity becomes very close to that of the frequency non-selective channel.

3. Computer Simulation

3.1 Simulation Condition

The downlink capacity is evaluated by Monte Carlo computer simulation. The simulation condition and cellular

 Table 1
 Simulation condition.

MC- CDMA	Data modulation		QPSK
	No. of subcarriers		N _c =256
	Guard interval		$N_g=32$
	Spreading	Channelization	OVSF codes
	code	Scrambling	PN code
	Spreading factor		SF=256
	Frequency-domain equalization		MMSE
	No. of receive antennas		M=1~4
	Channel estimation		Ideal
Site diversity	User distribution		Uniform
	Allowable outage probability		0.1
	Required BER		10-2
	Maximum no. of active BS's		D=1~7
	Threshold		$P_{th}=0\sim10 \text{ dB}$
Channel model	Path loss exponent		α=3~4
	Shadowing loss standard deviation		σ=4~10 dB
	Multipath	No. of paths	L=16
		Power delay profile	Exponential
	fading	Decay factor	γ=0~10 dB
		Time delay	Δ=1, 2



structure of 19 cells are shown in Table 1 and Fig. 4, respectively. We consider MC-CDMA using N_c =256 subcarriers and $N_g=32$ samples. An L=16-path Rayleigh fading having an exponential power delay profile with decay factor γ (i.e., $E[|\xi_{i.u(j),l}^{(m)}|^2] = (\frac{1-\gamma^{-1}}{1-\gamma^{-L}})\gamma^{-l}$ for $l = 0 \sim L - 1$) and $\tau_l = l \times \Delta$ samples for the *l*th path is assumed, where Δ is the time delay difference between adjacent paths. We assume an interference-limited environment, where the AWGN effect is negligible, and assume that each user receives interference only from six surrounding BS's. 18 cells surrounding the center cell are considered as co-channel cells. The user of interest is located in the center cell (0th cell). The BERs of all users are statistically equally-likely since we assume that users are uniformly distributed. Therefore, in the computer simulation, we only measure the BER distribution of the 0th user in the 0th cell to obtain the link capacity. The maximum number D of active BS's is $D=1\sim7$; D=1 means no site diversity operation and D=7 means that six cochannel cells surrounding the center cell are involved in the site diversity operation. Ideal channel estimation is assumed.

Normalized link capacity U/SF

0.2

0.15

0.05

0

2

Fig. 5 Effect of site diversity threshold P_{th} on the link capacity.

 P_{th} (dB)

6

4

 $\sigma=6dB$ $\gamma=0dB, \Delta=1$

D=7, M=1

 $\alpha = 3.5$

 $\dot{\alpha}=3$

8

10

In each simulation run, locations of U users per cell are generated. After generation of path losses and shadowing losses of all BS's to each user, active BS's are selected for each user for site diversity operation. Then, the number of active channels of each BS is determined. For signal transmission of the user of interest in the 0th cell, all the downlink channels experiencing independent L=16-path Rayleigh fading having an exponential power delay profile with decay factor γ are generated. Site diversity operation is carried out, followed by data-demodulation and the number of transmission errors is counted to measure the local average BER. In each simulation run, all users' locations are randomly changed and the distribution of local average BER is recorded. The simulation run is repeated sufficient times to measure the BER distribution. Using the BER measured distribution, the outage probability (the probability of local average BER larger than the required BER) is obtained for U users per cell. The outage probability increases as the number of users per cell increases. Starting from U=1, the above-described procedure is carried out by increasing the value of U by one, until the outage probability exceeds the allowable probability. The maximum number of users not exceeding the allowable outage probability is the link capacity. In this paper, we assume a required BER of 10^{-2} and an allowable outage probability of 0.1.

3.2 Effect of Site Diversity Threshold

The effect of site diversity threshold P_{th} on the downlink capacity normalized by *SF* and the site diversity user ratio (defined as the ratio of the total number of users) is plotted for *D*=7 in Figs. 5 and 6, respectively. The uniform power delay profile with γ =0 dB and Δ =1 is assumed. As was anticipated, there exists an optimum in P_{th} . When the threshold is too large, the number of users in site diversity op-





Fig. 6 Effect of site diversity threshold P_{th} on the site diversity user ratio.

eration increases, resulting in an excessive interference and hence, a decreased link capacity. The optimum threshold becomes larger with the increase in the path loss exponent α . This is because as α increases, the received signal power decreases and therefore, more BS's need to be involved in the site diversity operation. It is seen from Fig. 6 that as the threshold increases, the number of users in site diversity increases. The site diversity user ratio at the optimum threshold is about 30 percent irrespective of α .

3.3 Effects of Path Loss Exponent α and Shadowing Loss Standard Deviation σ

Figures 7 and 8 show the effects of path loss exponent α and shadowing loss standard deviation σ on the downlink capacity, respectively. The uniform power delay profile with $\gamma=0$ dB and $\Delta=1$ is assumed. The optimum threshold is used in each case. Also plotted in Figs. 7 and 8 are the simulation results without site diversity (D=1). As α increases, the link capacity increases. The reason for this can be as explained below. Since the path loss is proportional to the α -th power of the distance, the interference power from interfering BS's far from a user is attenuated more than the desired signal power from the active BS's closer to the user. Hence, as α increases, the desired signal-to-interference power ratio become higher, resulting in an increased link capacity under an interference-limited environment.

On the other hand, the link capacity is almost insensitive to the value of σ . As σ increases, variations in the interference power become larger and the probability of large interference becomes higher, reducing the link capacity. However, since the interference power variations from different BS's are independent, the site diversity effect due to BS selection increases. As a consequence, the link capacity becomes almost independent of the threshold.



Fig.8 Effect of shadowing loss standard deviation σ .

3.4 Effects of Decay Factor γ and Time Delay Difference Δ

So far, we have assumed the uniform power delay profile $(\gamma=0 \text{ dB})$ and 1 sample time delay $(\Delta=1)$. Here, we discuss the effects of decay factor γ and time delay difference Δ . Figure 9 shows the normalized link capacity as a function of γ . As γ increases, the channel frequency-selectivity becomes weaker and the frequency diversity effect reduces, resulting in a degraded BER performance. Consequently, the link capacity reduces irrespective of whether site diversity is used or not. The link capacity is plotted for $\Delta=1$ and



Fig.9 Effects of decay factor γ and time deference.



Fig. 10 Effect of allowable maximum number D of active BS's.

2 in Fig. 9. Since the GI of $N_g=32$ samples is used, the time delays of all the paths are within the GI when $\Delta=1$ and 2. It is known [11] that as far as all path time delays are within the GI, the BER performance is independent of Δ . Hence, the link capacity is independent of Δ when $\Delta=1$ and 2.

3.5 Effect of the Maximum Number D of Active BS's

So far, we have assumed D=7. The achievable link capacity depends on D. The effect of D is plotted in Fig. 10. As D increases from one, the site diversity effect becomes larger and hence, the link capacity increases. However, since the number of additional channels necessary for site diversity transmission increases, the interference power may also in-



Fig. 11 Probability of the number $n_{act} (\leq D)$ of active BS's selected from D=7 BS's.



Fig. 12 Performance improvement by antenna diversity.

crease and this reduces the link capacity. Therefore, an optimum value may exist in *D*. It can be seen from Fig. 10 that there is a broad optimum in *D* for $D=3\sim7$, however the optimum can be selected around D=3. A possible reason for this broad optimum in *D* is explained below. Figure 11 shows the probability of number $n_{act} (\leq D)$ of active BS's selected from *D* BS's when D=7. With the optimum threshold ($P_{th}=4.5$ dB in this case), the probability that more than three BS's are active is very small even when D=7. This suggests that when the optimum threshold P_{th} is used, the interference power may not increase that much. Therefore, almost the same capacity is obtained for D > 3. Figure 10 is for the case of path loss exponent $\alpha=3.5$. Note that we evaluated the effect of *D* on the link capacity for various values of α (α =3~4) to confirm that D=3 is sufficient irrespective of α when the optimum threshold is used.

3.6 Performance Improvement by Antenna Diversity

So far, we have assumed a single receive antenna at the mobile station. Antenna diversity improves the transmission performance in MC-CDMA [12]. Figure 12 shows the performance improvement by M-antenna diversity reception. The use of M-antenna diversity reception increases the link capacity by M times as in DS-CDMA.

4. Conclusion

In this paper, the downlink site diversity reception with MMSE-FDE and antenna diversity reception was considered for a MC-CDMA cellular system. The MMSE-FDE weight for joint site diversity and antenna diversity combining was derived. It was shown that similar to DS-CDMA cellular systems, site diversity can improve the downlink capacity. It was found that the sufficient number of active BS's to be involved in site diversity operation is 3 and that the link capacity can be maximized by the threshold that allows 30 percent of users to engage in site diversity operation. It was also found that use of antenna diversity in addition to the site diversity is effective to further increase the link capacity as in DS-CDMA cellular systems.

In this paper, only the downlink site diversity was evaluated. The study on the uplink site diversity is left as an important future study.

References

- [1] W.C. Jakes, Jr., ed., Microwave Mobile Communications, Wiley, New York, 1974.
- [2] S. Hara and R. Prasad, "Overview of multicarrier CDMA," IEEE Commun. Mag., vol.35, no.12, pp.126–133, Dec. 1997.
- [3] L. Hanzo, W. Webb, and T. Keller, Single- and multi-carrier quadrature amplitude modulation, John Wiley & Sons, 2000.
- [4] M. Helard, R. Le Gouable, J.-F. Helard, and J.-Y. Beaudis, "Multicarrier CDMA techniques for future wideband wireless networks," Ann. Telecommun., vol.56, pp.260–274, 2001.
- [5] H. Atarashi, S. Abeta, and M. Sawahashi, "Variable spreading factor-orthogonal frequency and code division multiplexing (VSF-OFCDM) for broadband packet wireless access," IEICE Trans. Commun., vol.E86-B, no.1, pp.291–299, Jan. 2003.
- [6] A.J. Viterbi, CDMA: Principles of spread spectrum communications, Addison Wesley, 1995.
- [7] S. Hara and R. Prasad, "Design and performance of multicarrier CDMA system in frequency-selective Reyleigh fading channels," IEEE Trans. Veh. Technol., vol.48, no.5, pp.1584–1595, Sept. 1999.
- [8] A. Chouly, A. Brajal, and S. Jourdan, "Orthogonal multicarrier techniques applied to direct sequence spread spectrum CDMA system," Proc. IEEE GLOBECOM'93, pp.1723–1728, Nov. 1993.
- [9] N. Maeda, H. Atarashi, S. Abeta, and M. Sawahashi, "Antenna diversity reception appropriate for MMSEC combining in frequency domain for forward link OFCDM packet wireless access," IEICE Trans. Commun., vol.E85-B, no.10, pp.1966–1977, Oct. 2002.
- [10] F. Adachi, M. Sawahashi, and K. Okawa, "Tree-structured generation of orthogonal spreading codes with different lengths for forward link of DS-CDMA mobile radio," Electron. Lett., vol.33, pp.27–28, Jan. 1997.

- [11] T. Sao and F. Adachi, "Comparative study of various frequency equalization techniques for downlink of a wireless OFDM-CDMA system," IEICE Trans. Commun., vol.E86-B, no.1, pp.352–364, Jan. 2003.
- [12] F. Adachi and T. Sao, "Joint antenna diversity and frequency-domain equalization for multi-rate MC-CDMA," IEICE Trans. Commun., vol.E86-B, no.11, pp.3217–3224, Nov. 2003.
- [13] D. Garg and F. Adachi, "Joint space-time transmit diversity and minimum mean square error equalization for MC-CDMA with antenna diversity recepion," IEICE Trans. Commun., vol.E87-B, no.4, pp.849–857, April 2004.
- [14] S. Haykin, Adaptive filter theory, 3rd ed., Prentice-Hall, 1996.

Appendix: MMSE Weight Derivation for Site Diversity Combining

Following Refs. [12], [13], we derive the MMSE weight for site diversity combining taking into account both the ICI and noise. In deriving the MMSE weight, we assume that all BS's are participating in the site diversity operation. The reference signal $s_{u(j)}(k)$, which is the sum of the signals transmitted from active BS's, is given by

$$s_{u(j)}(k) = \sum_{d=0}^{\infty} \sqrt{\frac{2S_{d,u(j)}}{SF}} \times \left(c_{u(j)}(k \mod SF) c_{scr_{\mathcal{A}}}(k) x_{u(j)} \left(\left\lfloor \frac{k}{SF} \right\rfloor \right) \right).$$
(A·1)

Using Eq. (4), the estimation error between the reference signal and the signal after joint site diversity and antenna diversity combining is given by

$$e(k) = s_{u(i)}(k) - A\boldsymbol{w}^{T}(k)\boldsymbol{R}(k)$$
(A·2)

with

$$\begin{cases} \boldsymbol{A} = [1, \cdots, 1] \\ \boldsymbol{w}(k) = \begin{bmatrix} c_{scr_{.0}}^{*}(k)w_{0.\iota(j)}^{(0)}(k), \cdots, c_{scr_{.\infty}}^{*}(k)w_{\infty.\iota(j)}^{(0)}(k) \\ \vdots & \ddots & \vdots \\ c_{scr_{.0}}^{*}(k)w_{0.\iota(j)}^{(M-1)}(k), \cdots, c_{scr_{.\infty}}^{*}(k)w_{\infty.\iota(j)}^{(M-1)}(k) \end{bmatrix} \\ \boldsymbol{R}(k) = \begin{bmatrix} R_{\iota(j)}^{(0)}(k), R_{\iota(j)}^{(1)}(k), \cdots, R_{\iota(j)}^{(M-1)}(k) \end{bmatrix}^{T}, \end{cases}$$
(A·3)

where the superscript *T* represents the transpose operation. The problem is to find the MMSE weight matrix w(k) that minimizes the mean square error (MSE) $E[|e(k)|^2]$. According to [14], w(k) must satisfy

$$\frac{\partial}{\partial \boldsymbol{w}(k)} E\left[\left|\boldsymbol{e}(k)\right|^2\right] = \mathbf{0}.$$
 (A·4)

Since the scrambling codes $\{c_{scr_d}(k)\}$ are independent, Eq. (A·4) is equivalent to

$$\frac{\partial}{\partial w_{d,u(j)}^{(m)}(k)} E\left[|e_d(k)|^2\right] = 0 \quad \text{for} \quad d = 0 \sim \infty, \quad (A \cdot 5)$$

where $e_d(k)$ is the estimation error with respect to the *d*th BS and is given by

$$e_{d}(k) = \sqrt{\frac{S_{d \perp u(j)}}{SF}} c_{u(j)}(k \mod SF) c_{scr \perp d}(k) x_{u(j)} \left(\left\lfloor \frac{k}{SF} \right\rfloor \right) - \sum_{m=0}^{M-1} \left[w_{d \perp u(j)}^{(m)}(k) c_{scr \perp d}^{*}(k) \sum_{i=0}^{\infty} H_{i \perp u(j)}^{(m)}(k) \times \left\{ \sqrt{\frac{2S_{i \perp u(j)}}{SF}} \sum_{u(i)=0}^{U_{i}-1} c_{u(i)}(k \mod SF) c_{scr \perp i}(k) x_{u(i)} \left(\left\lfloor \frac{k}{SF} \right\rfloor \right) \right\} + \Pi^{(m)}(k) w_{d \perp u(j)}^{(m)}(k) c_{scr \perp d}^{*}(k) \bigg|, \qquad (A \cdot 6)$$

which means that the MMSE weight for the *d*th active BS is equal to the weight that minimizes the MSE between the received signal and the signal transmitted from the *d*th active BS. Substituting Eq. $(A \cdot 6)$ into Eq. $(A \cdot 5)$ gives

$$\sum_{i=0}^{\infty} \Gamma_{i,\mu(j)} U_i H_{d,\mu(j)}^{(m)*}(k) \left[\sum_{m=0}^{M-1} H_{i,\mu(j)}^{(m)}(k) w_{d,\mu(j)}^{(m)}(k) \right] \\ + SF w_{d,\mu(j)}^{(m)}(k) - \Gamma_{d,\mu(j)} H_{d,\mu(j)}^{(m)*}(k) = 0$$
(A·7)

for all k and m, where $\Gamma_{i \perp u(j)} = S_{i \perp u(j)}T_cN_c/N_0$ is the averaged received signal energy per symbol-to-the AWGN power spectrum density ratio. After some manipulations [12], [13], we obtain

$$w_{d,u(j)}^{(m)}(k) = \frac{\Gamma_{d,u(j)}H_{d,u(j)}^{(m)*}(k)}{\sum_{i=0}^{\infty}\Gamma_{i,u(j)}U_{i}\sum_{m=0}^{M-1}\left|H_{i,u(j)}^{(m)}(k)\right|^{2} + SF}.$$
 (A·8)

In the above, we have assumed that all BS's are participating in the site diversity operation. However, only some of the BS's provide sufficient power to a user in the site diversity operation and hence, we introduce the threshold P_{th} to select a limited number of BS's as active BS's for avoiding excessive interference increase as well as reducing the complexity. In this paper, the number of active BS's is limited to *D* at maximum.

Note that the denominator of Eq. $(A \cdot 8)$ is the instantaneous received power of the *k*th subcarrier. Therefore, the MMSE weight can be computed by carrying out channel estimation only for active BS's and the instantaneous power measurement of each subcarrier based on the received pilot symbols periodically transmitted from each BS.



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