# Analysis of Downlink Wideband DS-CDMA Systems with Smart Antenna for Different Spreading Bandwidths in Wideband Multipath Channel

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## Abstract

In this paper, the Eigen-RAKE receiver in wideband direct sequence code-division multiple access(DS-CDMA) systems with downlink smart antenna is analyzed for different spreading bandwidths(1.25 MHz, 5 MHz, 10 MHz) and different channel environments(macro, micro). The realistic spatio-temporal wideband multipath channel is assumed, one of which is standardized multiple-input single-output(MISO) radio channel model for WCDMA link-level simulations proposed by 3$^{rd}$ generation partnership project(3GPP) contributions. We assumed spatial scattering phenomenon in which many unresolvable path signals within a limited range of spatial angle simultaneously contribute to the signals received at the receiver. Several multipaths within one chip are distinguished into each one and the first multipath components are selected as the desired signal and the others are considered self-interference. Downlink DS-CDMA system with eigenbeamformer using wider bandwidth present better performance than that using narrow bandwidth system by employing Eigen-RAKE receiver of many number of branches. It is shown that the downlink eigenbeamformer is more effective in typical urban macro cellular environments when using Eigen-RAKE receiver.

***Key words*** : Beamforming(BF), Direct Sequence Code-Division Multiple Access(DS-CDMA), Eigen-RAKE Receiver, Spreading Bandwidths.

## Ⅰ. Introduction

In CDMA system, multiple users use different code sequences to share the same frequency band at the same time. Because of the imperfect orthogonality among the different code sequences, multiple access interference(MAI) is a major limitation to the channel capacity[1]. Future wireless communication systems will be characterized by high data rate services accessible for a large number of users. Especially the downlink must be able to cope with considerable traffic loads in order to facilitate new multimedia information services like wireless internet or video on demand. In this context, downlink beamforming with antenna arrays is promising means to improve the overall system capacity and to overcome the limited bandwidth[2].

Using an antenna array, the amount of interference can be considerably reduced by steering nulls of beam pattern towards the directions of dominant interferer.

In this paper, we present analysis of Eigen-RAKE receiver in downlink wideband CDMA systems with eigenbeamformer for three different bandwidths and different two channel environments(macro, micro). In conventional analysis, performance of beamforming system has been analyzed with assumption that the received signal within one chip duration becomes only one multipath from a certain direction in space regardless of signal bandwidth. So we couldn't exactly analyze the effect of different bandwidths. Several multipaths within one chip are distinguished into each one and the first multipath components are selected as the desired signal and the others are considered self-interference[3].

The paper is organized as follow. The spatial channel modeling is outlined in Section II. The W-CDMA downlink model is treated in Section III. Section IV provides simulation results. Finally the paper is concluded in Section V.

## Ⅱ. Spatial Channel Modeling

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In this paper, we assumed that the base station(BS) is equipped with the uniform linear array(ULA) containing $M$ elements, spaced $\lambda/2$ apart. Mobile stations (MS) use a single antenna. $\lambda$ means the wavelength of the downlink carrier signal.

Fig. 1 shows channel impulse response of spatio-temporal downlink vector channel model. Each of these resolvable paths will in reality be cluster of temporally unresolvable sub-multipaths. Sub-multipaths of a cluster are assumed to have different directions within an angular spread $\Delta$ with respect to the main angle of departure(AOD) $\theta$ [4]. In Fig. 1, $\tau_{k,v}^{\langle n\rangle}$ means $v^{th}$ path's delay of $k^{th}$ user within $n^{th}$ chip duration, where $v$=1, $\cdots$, $s_n$, and $s_n$ is the number of path within $n^{th}$ chip duration.

Although the BS transmits signals in all directions over $[-\pi/3,\ \pi/3]$, only signals whose angle of departures(AOD) lie in a certain range, $[\theta-\Delta/2,\ \theta+\Delta/2]$, contribute to received signals at the MS due to MS and scatterers locations, where $\Delta$ is the standard deviation of the angular spread(AS) caused by the scatterers, which surround the MS and scatter the signals. The distribution of scatters is modeled as a Laplacian distribution in azimuth with mean $\theta$ and standard deviation $\Delta$. The scatterers are grouped into clusters in space, and each cluster is associated with a resolvable path of the frequency selective multipath channel. The $M$(the number of antenna elements) dimensional spatial downlink channel vector of $v^{th}$ path of $k^{th}$ user within $n^{th}$ chip duration is modeled as follows

$$\rho_{k,v}^{<n>}(t) = \sqrt{\frac{P_{k,v}^{<n>}}{L_{k,v}^{<n>}}} \sum_{l=1}^{L_{k,v}^{<n>}} e^{j\phi_{k,v,l}^{<n>}} \mathbf{a}(\theta_{k,v,l}^{<n>}) \qquad (1)$$

where $P_{k,v}^{\langle n\rangle}$ is the tap power, $L_{k,v}^{\langle n\rangle}$ is the number of scattered signals contributing to the $v^{th}$ path tab of $k^{th}$ user within $n^{th}$ chip duration, $\phi_{k,v,l}^{\langle n\rangle}$ is the random phase of each scattering component uniformly distributed on (0, $2\pi$)[5]. $a(\theta_{k,d,l}^{\langle n\rangle})$ is a downlink array response vector caused by the direction of the $l^{th}$ scatterer in the $v^{th}$ path of $k^{th}$ user within $n^{th}$ chip duration. Also, this value is determined by the structure of transmit antenna array.

$$\mathbf{a}(\theta) = [e^{j\varphi_1}\ e^{j\varphi_2}\ \cdots\ e^{j\varphi_M}] \qquad (2)$$

$M$ is the total number of antenna elements, $\varphi_m$ is equal to $\frac{2\pi}{\lambda} d_{1,m} \sin(\theta)$, and $d_{1,m}$ represents the space between the $1^{st}$ antenna element and the $m^{th}$ antenna element.

## III. W-CDMA Downlink Model

### 3-1 Base Station Model

Fig. 2 shows the configuration of base station transmit antenna arrays in downlink. The BS transmits signals $s_k(t)=c_k(t)\,d_k(t)$ for different $K$ users simultaneously, where $c_k(t)$ and $d_k(t)$ are the $k^{th}$ user's spreading sequences with chip duration $T_c$ and the $k^{th}$ user's data with symbol duration $T_d$, respectively.

We assumed that the base station controls the weight vector $\mathbf{w}_k = [w_{k,1}\ w_{k,2}\ \cdots\ w_{k,M}]^T$ based on the downlink beamforming method. By a baseband equivalent model expression, the $k^{th}$ user's transmitted signal at the $m^{th}$ antenna is described as

$$s_{k,m}(t) = w_{k,m} s_k(t) = \sqrt{P_k} w_{k,m} b_k(t) c_k(t), \qquad (3)$$

where $w_{k,m}$ is the $m^{th}$ element of the $k^{th}$ user's $M$ by 1 downlink beamforming weight vector, $\mathbf{w}_k$, and $p_k$ denote the transmit power of the $k^{th}$ user respectively. In order

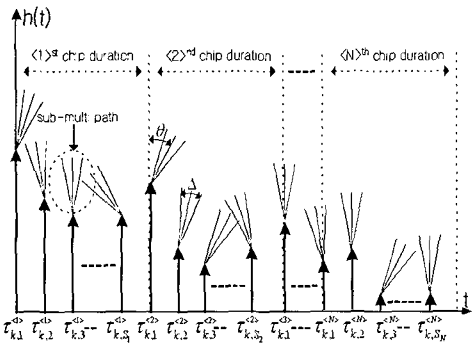


Fig. 1. Channel impulse response of spatio-temporal downlink vector channel model.

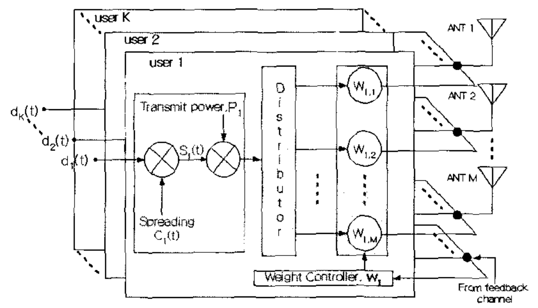


Fig. 2. Transmitter structure of the transmit beamforming system.

to avoid additional transmit power gain, $w_{k,m}$'s are normalized to $\| \mathbf{w}_k \|^2 = \sum_{m=1}^{M} |w_{k,m}|^2 = 1$[6].

The total transmit signals from BS antenna array are written as

$$\mathbf{s}(t) = \sum_{u=1}^{U} \sqrt{P_u} c_u(t) d_u(t) \mathbf{w}_u^*, \tag{4}$$

where $U$ is the number of users in the cell-site, and * denotes complex conjugate.

## 3-2 Receiver Model

The received signal of the $k^{th}$ user is given by eq.(5).

$$r_k(t) = \sum_{u=1}^{U} \sum_{n=1}^{N} \sum_{v=1}^{S_n} (\boldsymbol{\rho}_{u,v}^{<n>})^T \mathbf{w}_u s_u(t-\tau_{u,v}^{<n>}) + \mathbf{n}_k(t), \tag{5}$$

where $N$ is the number of available chip duration, and $s_n$ is the number of path within $n^{th}$ chip duration. $\rho_{u,v}^{\langle n\rangle}$ and $\tau_{u,v}^{\langle n\rangle}$ denote the downlink channel vector and time delay corresponding to the $v^{th}$ path of $u^{th}$ user within $n^{th}$ chip duration, respectively. And $\mathbf{w}_u$ is a beamforming weight vector for the $u^{th}$ user.

Fig. 3 shows a receiver structure. The $k^{th}$ user has N-finger Eigen-RAKE receiver. We assume that first paths of $k^{th}$ user within $n^{th}$ chip duration are desired signal.

After the despreading processing, the decision variable for the $q^{th}$ symbol at the output of the $n^{th}$ Eigen-RAKE finger is

$$\begin{aligned} z_k^{<n>}(q) &= \int_{qT_s+\tau_{k,1}^{<n>}}^{(q+1)T_s+\tau_{k,1}^{<n>}} r_k(t) c_k(t-\tau_{k,1}^{<n>}) dt \\ &= b_k PGT_c \sqrt{P_k} (\boldsymbol{\rho}_{k,1}^{<n>})^T \mathbf{w}_k + SI_k^{<n>}(q) + I_k^{<n>}(q) + n_k^{<n>}, \end{aligned} \tag{6}$$

where $\boldsymbol{\rho}_{k,1}^{<n>}$ is the $M$ by 1 desired multipath channel vector of the downlink. The processing gain is expressed by $PG$. $SI_k^{\langle n\rangle}(q)$, $I_k^{\langle n\rangle}(q)$ and $n_k^{\langle n\rangle}$ the outputs corresponding to self-interference, multiple access interference for $k^{th}$ user and the background noise, respectively, at the $n^{th}$ Eigen-RAKE finger.

At the Eigen-RAKE receiver, the outputs of symbol integrators are combined with the multipath combining weight vector, $G_k = [G_k^{\langle 1\rangle}\ G_k^{\langle 2\rangle} \ldots G_k^{\langle N\rangle}]^T$, and the combined output is given by

$$\begin{aligned} z_k(n) &= \sum_{n=1}^{N} G_k^{<n>*} z_k^{<n>}(q) = \mathbf{G}_k^H \mathbf{z}_k(q) \\ &= b_k PGT_c \sqrt{P_k} \mathbf{G}_k^H \boldsymbol{\rho}\, \mathbf{w}_k + \mathbf{G}_k^H \mathbf{SI}_k(q) + \mathbf{G}_k^H \mathbf{I}_k(q) + \mathbf{G}_k^H \mathbf{n}_k(q), \end{aligned} \tag{7}$$

where $\mathbf{z}_k(q)$ is a N by 1 decision variable vector. $\mathbf{SI}_k(q)$, $\mathbf{I}_k(q)$ and $\mathbf{n}_k(q)$ are N by 1 self-interference vector, multiple access interference vector and noise vector, respectively. $\boldsymbol{\rho} = [\boldsymbol{\rho}_k^{<1>}\ \boldsymbol{\rho}_k^{<2>} \text{利}\cdot \boldsymbol{\rho}_k^{<N>}]^T$ is a N by M channel matrix. N is the number of Eigen-RAKE fingers.

The $k^{th}$ user's SINR of combined output is given by the following equation.

$$\gamma_k = \frac{(PGT_c)^2 P_k \mathbf{w}_k^H \boldsymbol{\rho}^H \mathbf{G}_k \mathbf{G}_k^H \boldsymbol{\rho}\, \mathbf{w}_k}{\mathrm{var}(\mathbf{SI}(q)) + \mathrm{var}(\mathbf{I}(q)) + \mathrm{var}(\mathbf{n}(q))}. \tag{8}$$

The variance of self-interference caused by multipaths is

$$\begin{aligned} \mathrm{var}(\mathbf{SI}(q)) &= \mathbf{G}_k^H E[\mathbf{SI}_k(q) \mathbf{SI}_k^H(q)] \mathbf{G}_k \\ &= \frac{PG}{2} T_c^2 P_k \mathbf{w}_k^H \boldsymbol{\rho}_{SI}^H \mathbf{G}_k \mathbf{G}_k^H \boldsymbol{\rho}_{SI} \mathbf{w}_k \\ &= \frac{PG}{2} T_c^2 P_k \left\| \mathbf{G}_k^H \boldsymbol{\rho}_{SI} \mathbf{w}_k \right\|^2, \end{aligned} \tag{9}$$

where $\| \cdot \|$ is vector norm, and $[\cdot]$ denotes expectation. Self-interference channel vector of a desired user is defined as

$$\boldsymbol{\rho}_{SI} = [\sum_{v=2}^{S_1} \boldsymbol{\rho}_{k,v}^{<1>} \sum_{v=2}^{S_2} \boldsymbol{\rho}_{v,s}^{<2>} \cdots \sum_{v=2}^{S_N} \boldsymbol{\rho}_{v,s}^{<N>}]^T. \tag{10}$$

The variance of multiple access interference due to the other users in the same cell is

$$\begin{aligned} \mathrm{var}(\mathbf{I}(q)) &= \mathbf{G}_k^H E[\mathbf{I}_k(q) \mathbf{I}_k^H(q)] \mathbf{G}_k \\ &= \sum_{u=1, u\neq k}^{U} \frac{2PG}{3} T_c^2 P_u \mathbf{w}_u^H \boldsymbol{\rho}_I^H \mathbf{G}_k' \mathbf{G}_k^{H'} \boldsymbol{\rho}_I \mathbf{w}_u \\ &= \sum_{u=1, u\neq k}^{U} \frac{2PG}{3} T_c^2 P_u\ \mathbf{G}_k^{H'} \boldsymbol{\rho}_I \mathbf{w}_u{}^2. \end{aligned} \tag{11}$$

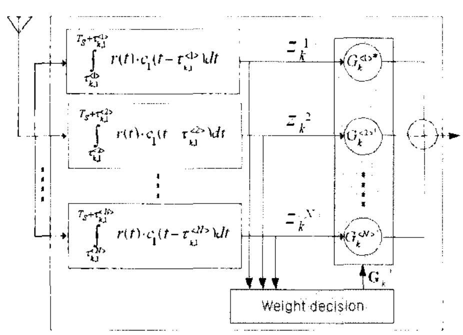


Fig. 3. Eigen-RAKE receiver.

where, $G_k'$ and $\rho_l$ are defined as following equations[7].

$$G_k' = [\sum_{n=1,n\neq 1}^{N} G_{k,s}^{<n>} \sum_{n=1,n\neq 2}^{N} G_{k,s}^{<n>} \cdots \sum_{n=1,n\neq N}^{N} G_{k,s}^{<n>}]^T. \quad (12)$$

$$\rho_l = [\sum_{v=1}^{S_1} \rho_{k,v}^{<1>} \sum_{v=1}^{S_2} \rho_{v,s}^{<2>} \cdots \sum_{v=1}^{S_N} \rho_{v,s}^{<N>}]^T. \quad (13)$$

The noise variance is given by following equation.

$$\begin{aligned} \mathrm{var}(\mathbf{n}(q)) &= \mathbf{G}_k^H E[\mathbf{n}_k(q)\mathbf{n}_k^H(q)]\mathbf{G}_k \\ &= (PG\cdot T_c)^2 \|\mathbf{G}_k\|^2 \sigma_k^2. \end{aligned} \quad (14)$$

### 3-3 Adaptive Procedure

The weight vector in the closed-loop mode system can be acquired from the common pilot channel (CPICH), whose signal is received separately from each antenna element. In order to form a beam toward each user, beamforming weight should be calculated to maximize the SINR or SNR. The mean downlink channel correlation matrix(CCM) $\mathbf{R}_{k,1}^{\langle n\rangle}$ of $1^{th}$ downlink path tap of $k^{th}$ user within $n^{th}$ chip duration is obtained as $\mathbf{R}_{k,1}^{\langle n\rangle} = E[\rho_{k,1}^{\langle n\rangle}(t)\,\rho_{k,1}^{\langle n\rangle}(t)^H]$, where $H$ superscript denote complex conjugate transpose. It's eigenvalue decomposition(EVD) will play an important role in analyzing the performance of some of the algorithms. By performing the EVD of $\mathbf{R}_{k,1}^{\langle n\rangle}$, we express it as a function of its eigenvalues and eigenvectors

$$\mathbf{R}_{k,1}^{<n>} = \mathbf{U}\mathbf{E}\mathbf{U}^H = \sum_{i=1}^{M} e_i(\mathbf{u}_i\mathbf{u}_i^H), \quad (15)$$

where $\mathbf{E}$ is a diagonal matrix whose diagonal entries are equal to the corresponding eigenvectors $\mathbf{u}_1, \mathbf{u}_2, \cdots, \mathbf{u}_M$ [5].

In case of frequency selective fading with $N$ taps, the mean CCMs of all downlink taps are summed following equation[5].

$$\mathbf{R}_{k,1}^{sum} = \sum_{n=1}^{N} \mathbf{R}_{k,1}^{<n>}. \quad (16)$$

In this paper we used the principal eigenvector of the downlink CCM $\mathbf{R}_{k,1}^{sum}$ as beamformer, and beamforming weight vector $\mathbf{w}_k^H$ is used the unit-norm principal eigenvector $\mathbf{u}_{\max}$ of $\mathbf{R}_{k,1}^{sum}$. Also $n^{th}$ Eigen-RAKE combining weight $G_k^{<n>} = (\rho_{k,1}^{<n>})\mathbf{w}_k$, therefore Eigen-RAKE combining weight vector is

$$\mathbf{G}_k = [G_k^{<1>}\ G_k^{<2>} \cdots G_k^{<N>}] = \rho\, \mathbf{w}_k. \quad (17)$$

Then we can rewrite eq.(8) as eq.(18)

$$\gamma_k = \frac{P_k \|\rho\, \mathbf{w}_k\|^4}{\frac{1}{2PG} P_k \|\mathbf{G}_k^H \rho_{sl} \mathbf{w}_k\|^2 + \sum_{u=1,u\neq k}^{U} \frac{2}{3PG} P_u \|\mathbf{G}_k^{H'} \rho_l \mathbf{w}_u\|^2 + \|\rho\, \mathbf{w}_k\|^2}. \quad (18)$$

## Ⅳ. Simulations

In this paper, we carry out simulation for proposed W-CDMA systems in realistic spatio-temporal wideband channel, one of which is standardized MISO radio channel model for WCDMA link-level simulations proposed by 3GPP contributions. We use the eigenvalue decomposition to form a beam pattern. The major downlink radio parameters of the simulations are listed in Table 1.

We assume all transmitted data as +1. Also we assume that code synchronization and channel estimation are perfect. And we don't use a channel coding. All systems considered transmit unit power for fair comparison. Perfect channel estimation at the MS is assumed.

The parameters of the MISO model are summarized in Table 2. Pedestrian A corresponds to typical urban macro cellular environments, where the angle of departure(AOD) is assumed to be identical for all delays. Pedestrian B corresponds to micro-cellular and bad urban environments, assuming different AOD for different delays. Power delay profiles refer to ITU models[8].

We generate the signals of one hundred interfering users whose distribution is random between [$-\pi/3$, $\pi$

Table 1. Radio link parameters of the simulation.

| System bandwidth | 1.25 MHz | 5 MHz | 10 MHz |
|---|---|---|---|
| Carrier frequency (Downlink) | 1.95 GHz | 1.95 GHz | 1.95 GHz |
| Symbol rate | 125 kbps | 125 kbps | 125 kbps |
| Modulation | QPSK | QPSK | QPSK |
| Processing gain | 10 | 40 | 80 |
| Total number of RAKE branch(Pedestrian A) | 1 | 2 | 3 |
| Total number of RAKE branch(Pedestrian B) | 4 | 6 | 6 |
| Weighting algorithm | EVD | EVD | EVD |

Table 2. Summary of MISO channel models.

| Tap | Pedestrian A | | | Pedestrian B | | |
|---|---|---|---|---|---|---|
| | Delay (ns) | Power (dB) | AOD | Delay (ns) | Power (dB) | AOD |
| 1 | 0 | 0 | 20° | 0 | 0 | 2° |
| 2 | 110 | - 9.7 | 20° | 200 | - 0.9 | - 20° |
| 3 | 190 | - 19.2 | 20° | 800 | - 4.9 | 10° |
| 4 | 410 | - 22.8 | 20° | 1200 | - 8.0 | - 8° |
| 5 | N/A | N/A | N/A | 2300 | - 7.8 | - 33° |
| 6 | N/A | N/A | N/A | 3700 | 23.9 | 31° |
| PAS | Laplacian, AS=5° | | | Laplacian, AS=15° | | |

/3], and 20 sub-multipath signals are generated for respective multipaths. We used first multipath in each chip duration for the suitable signal of desired user because it is the strongest.

Fig. 4 illustrates the BER performances of 5 MHz system as a function of the angular spread of the desired signal for 30 interfering users in pedestrian A. As shown in the figure, spatial scattering degrades beamforming performance as the angular spread increases. On the other hand, as the angular spread(AS) increases, the performance of beamforming is degraded since the eigenbeamformer forms a wider beam with less gain. From this result we can expect that the downlink eigenbeamformer is more effective in cellular environments with small AS when using RAKE receiver.

Fig. 5 shows the result of simulation that represents average SINR comparison among three bandwidth systems by the number of interfering users in typicalurban macro cellular environments. We know that the performance of wider bandwidth system is superior to that of narrow bandwidth system in pedestrian A.

Fig. 6 is the result of simulation that represents average SINR comparison among 1.25 MHz, 5 MHz and 10 MHz system in micro-cellular and bad urban environments. We know that the performance of wider bandwidth system is superior to that of narrow bandwidth system, and as the number of interfering users is increased, the average SINR is decreased.

From Fig. 5 and Fig. 6, we know that the performance of pedestrian A is better than that of pedestrian B for all systems. This is because the angular spread of pedestrian A is smaller than that of pedestrian B. As angular spread increases, the performance of BF is degraded since the eigenbeamformer forms a wider beam with less gain. Also, we know that the average SINR of wider bandwidth system is higher than that of narrow bandwidth system by employing Eigen-RAKE receiver of many number of branches.

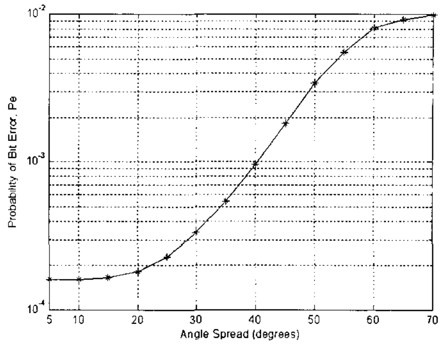


Fig. 4. The probability of bit error according to the angular spread. (5 MHz system, pedestrian A, 30 interfering users).

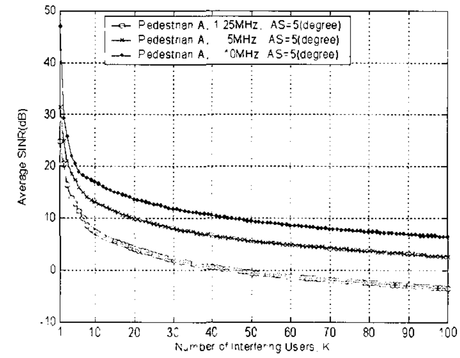


Fig. 5. The SINR comparison among 1.25 MHz, 5 MHz and 10 MHz system in pedestrian A.

Fig. 7 is the result of simulation that represents BER comparison among three systems in pedestrian A. A 10 MHz system using the Eigen-RAKE receiver of three branches shows better performance than 5 MHz system and 1.25 MHz system using two branches and one branch of the Eigen-RAKE receiver. All systems use MRC combining diversity.

Fig. 8 is the result of simulation that represents BER comparison among three systems in pedestrian A. A 10 MHz system using the Eigen-RAKE receiver of six branches shows better performance than 5 MHz system and 1.25 MHz system using the Eigen-RAKE receiver of six branches and four branches. All systems use MRC combining diversity.

Table 3. shows the number of interfering users acceptable BER=$10^{-3}$ from Fig. 7 and Fig. 8. For fixed

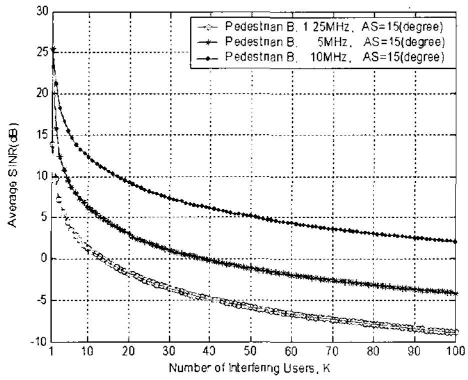


Fig. 6. The SINR comparison among 1.25 MHz, 5 MHz and 10 MHz system in pedestrian B.

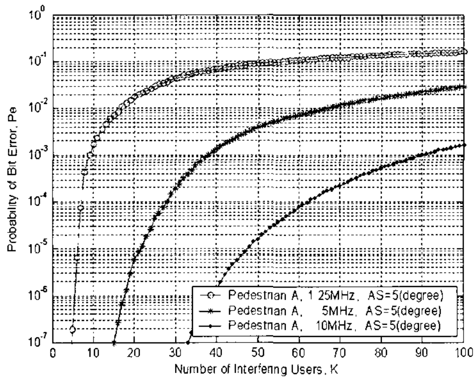


Fig. 7. Comparison of error probability vs. number of interfering users in pedestrian A.

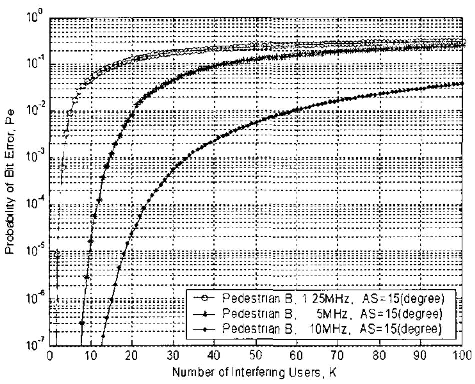


Fig. 8. Comparison of error probability vs. number of interfering users in pedestrian B.

BER=$10^{-3}$ the maxium number of allowable interfering users for 10 MHz system is more than 8 times(10 times in Pedestrian A & 11 times in Pedestrian B) than that of 1.25 MHz system and is more than 4 times(4.2 times in Pedestrian A & 4.6 times in Pedestrian B) than that

Table 3. The number of interfering users acceptable BER=$10^{-3}$ from Fig. 7 and Fig. 8.

| Channel environments | System bandwidth | | |
|---|---|---|---|
| | 1.25 MHz | 5 MHz | 10 MHz |
| Pedestrian A | 9 users | 38 users | 90 users |
| Pedestrian B | 3 users | 14 users | 33 users |

of 5 MHz system. Therefore downlink DS-CDMA system with eigenbeamformer using wider bandwidth shows additional performance enhancement as well as the performance increasing by bandwidth expansion in both channel environments.

## V. Conclusion

In this paper, we compared the performance of three systems having different system bandwidths for different channel environments(macro, micro) in downlink. We select the first multipath in each chip duration as the suitable received signal of desired user and the others are considered self-interference. We know that the performance of wider bandwidth system using downlink eigenbeamformer shows better performance than narrower bandwidth system by employing Eigen-RAKE receiver of many number of branches. Also, we verify that the performance of downlink DS-CDMA system with eigenbeamformer in typical urban macro cellular environments is considerably improved as shown in the result of simulation. Therefore, we will expect that better service can be provided by using the downlink eigenbeamformer in cellular environments with small angular spread(AS) and narrow distribution of angle of departure(AOD) for wide bandwidth system, and this feature makes future mobile communication system handle heavy traffic data or offer larger capacity.

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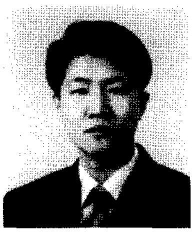

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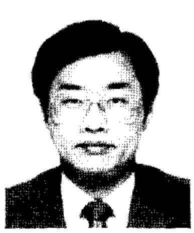

He received B.S., M.S. degrees in electronics engineering from Seoul National University, Korea in 1977 and 1979, respectively, and Ph.D. degree from University of Arizona, Tucson, Arizona, USA in 1987. From 1979 to 1983, he was a member of Research Staff at the Agency for Defense Development, Korea. From 1987 to 1989, he was with Electronics and Telecommnications Research Institute(ETRI) in Daejeon, Korea. Since 1989, he has been Professor of the School of Electronics, Computer & Information Engineering, Chonnam National University, Gwangju, Korea. His research interests include mobile communication systems, CDMA, and digital communication theory.