Space Time Rake Receivers for Time Division Synchronous CDMA Base Stations

Yang Xiao[1] · Kwang-Jae Lee[2] · Moon-Ho Lee[3] · Sam-Goo Cho[4]

Abstract

In this paper, we develop space-time(ST) Rake receivers for Time Division Synchronous Code Division Multiple Access(TD-SCDMA) base stations(BS). The beamforming of BS transforms the uplink MIMO channel space into many sub-sectors' channels to be nearly orthogonal, thus, well established 1-D Rake technology can be used to TD-SCDMA base station to construct ST Rake, which simplified the system's implementation as well as enlarged users' capacity by the beamforming. The construction and capacity of MIMO sub-sectors by multi-beamforming have been presented. The proposed ST Rake algorithm include the multi-beamforming algorithm for MIMO sub-sectors and classical 1-D Rake algorithm. The calculating formulas for interference plus noise ratio(SINR) and bit error rate(BER) have been derived. Simulations verify that the proposed ST Rake receiver for BS is effective, and the BS systems can get higher system capacity and can be of better performance than presented TD-SCDMA systems.

Key words : Space-Time, Rake Receivers, CDMA Systems, Array Antennas, Multi-Beamforming, MIMO Sub-Sectors.

Ⅰ. Introduction

When CDMA base stations equip with array antennas, the mobile stations can be identified by their different spatial signature vectors(SSVs)[1]~[3]. However, it is difficult to implement CDMA systems to provide each user one independent space beam (spatial channel), because of the huge complexity and high cost of the implementation of the systems. Therefore, CDMA2000 and WCDMA have not adopted space multi-beamforming technique for their array antennas, but turn to Space-Time spreading technique. Only TD-SCDMA systems used the space multi-beamforming technique for their array antennas[4], but TD-SCDMA systems did not consider ST Rake receivers for their BSs, which limited their communication quality and capacity[3]. The presented TD-SCDMA systems in [4] can only support 48 users for one carrier, and not consider increasing users capacity by space time processing[3],[5].

Though many papers have developed different schemes for ST Rake receivers[6]~[11], they have ignored three problems: the first is that applying ST Rake to presented CDMA protocols can not change their system structure and complexity obviously, the second is to increase the system capacity with the ST Rake, the third is that the spatial phase information should be lost by the processing of the Rake receivers[1]~[3]. The ST Rake schemes of many presented papers are first Rake processing then beamformer processing, however, the spatial phase information in the Rake processing has been lost. A further problem is that the schemes need every antenna element output to have a Rake receiver, which implies high cost and complexity of BS.

To solve the problem, we propose a simplified ST Rake receivers for the TD-SCDMA BS combining presented Rake receivers[12], which can reduce a lot of hardware of the systems which are necessary for [6]~[11], and depend on much more digital signal processing software. Compared with presented applicable CDMA systems, the narrow beamforming by using antenna arrays in proposed TD-SCDMA BS can divide the mobile users' signals in many sub-sectors of a cell, which means that one beam will be shared by many users instead of one user like [4], and leads to our MIMO sub-sector concept.

Based on the beamforming, the paper presents a ST Rake receivers algorithm to identify a mobile station by their waveform signature and spatial signature, similar to 2-D signal filtering[1]~[3]. The Space-Time Rake receivers can determine the attenuation of interference from different sectors in a cell, by analyzing the array pattern of the array antenna and SSVs of CDMA signals. Limited by the paper size, we only consider a synchronous uplink CDMA channel.

The paper is organized as follows. In section 2, we study the array pattern and MIMO sub-sectors. In sec-

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[1] Institute of Information Science, Beijing Jiaotong University, Beijing, China.
[2] Dept. of Multimedia, Information and Telecommunication, Hanlyo University, Chonnam, Korea.
[3] Dept. of Information and Communication, Chonbuk National University, Chonbuk, Korea.
[4] SoC Center of Korean Electronics Technology Institute, Seoul, Korea.

tions 3, the space-time Rake receivers are introduced. In section 4, we give the spatial weights calculation for beamformers of BS. In section 5, we study the properties of the ST Rake receivers and derive the calculating formula of SINR(Signal Interference Noise Ratio) and BER(Bits Error Ratio) of proposed ST Rake. The simulation results are presented in section 6, and Section 7 offers some conclusions.

Ⅱ. The Smart Antenna Structure and Proposed MIMO Sub-Sectors

The proposed TD-SCDMA with ST Rake is mainly based on the smart antenna technology shown in Fig. 1, the difference with the original scheme of [4] is in three hands: the first is that we change the order of despreading block and beamforming block, the second is that the original despreading block with Rake to despread the output signals of beamformer, and the third is that we also change the order of spreading block and beamforming block for the transmitting part. The smart antenna array is composed of antenna elements, related feed cables and coherent RF transceivers in RF part. By use of the A/D converters or D/A converters in analog baseband(ABB), the Rx and Tx analog signals are interfaced to the digital baseband(DBB) part over the high-speed data bus. In this model, all antenna elements related feed cables and coherent RF transceivers will be calibrated before operating.

Reference to Fig. 1, the base station is equipped with smart antenna array and DBB DSP[4]. When a signal comes from one mobile user within the coverage of the cell, each antenna element and coherent RF receiver will get it. Because of the different location of the different antenna element, the phase of the Rx signal will be different. In case of multipath propagation, each path will come from different directions with different amplitude and delay. Then the Rx signal at each antenna element will show different phase and amplitude. After the front-end processing in RF part and A/D converters processing in ABB, digitized Rx signal with the phase and amplitude information will be sent to DSP in DBB part. In a TD-SCDMA cellular system, there are many mobile users working simultaneously. The Rx signals will be the sum of the signals (including main path and multipath) coming from all the active mobile users within the cell and the interference coming from nearby cells.

To simplify the antenna array system of the TD-SCDMA systems[4], in this paper, we only use three linear antenna arrays to divide spatial domain of a cell into 3 sectors, [0°, 120°], [120°, 240°], [240°, 360°] shown as Fig. 2. To simplify questions, we directly use to denote the spatial signature vector(SSV) of one sector to a single unite amplitude signal with

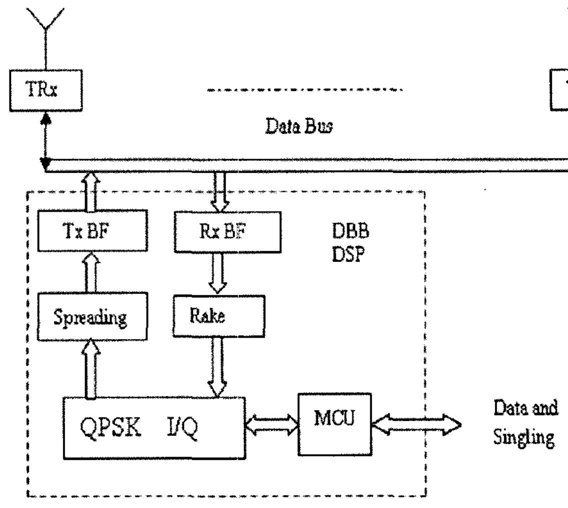

Fig. 1. Physical channel structure of TD-SCDMA.

$$a(\theta) = [1, e^{j\frac{2\pi d \sin\theta}{\lambda}}, \ldots, e^{j\frac{2\pi d(N-1)\sin\theta}{\lambda}}]^T \tag{1}$$

where λ denotes the wavelength of the RF signals received from antenna elements, θ denotes DOA, d is the interval between the two sensors of array antennas, and L is the number of sensors of linear array antennas of the sector.

Triangle antenna array we proposed for TD-SCDMA base stations is composed of 8 array elements in the three linear antenna arrays, which is shown in Fig. 2. At the inboard of antenna arrays, there are three metal clapboards, which decrease the linear array antennas to couple each other. Hence, the spatial domain of a cell is divided into three main MIMO sectors by three linear antenna arrays, [0°, 120°], [120°, 240°], [240°, 360°].

The antenna array in each sector is divided into Q sub-sectors, which have degrees as follows,

$$\triangle = 120°/Q$$

For simplify, we suppose that the linear array in each sector has 8 array elements and the interval between any array elements is $\lambda/2$. Then the antenna array pattern is given in Fig. 3. The width of center lobe of the array is as follows

$$BW_{0.5} = 0.866\frac{\lambda}{Nd} \cdot \frac{180°}{\pi} = 12.4045° \tag{2}$$

where, N is the number of array element in each sector, that is to say, N=8.

Compared with the previous smart antenna in TD-

SCDMA in [4] beyond the beam pattern 30 degrees, the current least beam pattern as shown in Fig. 3 can gains 12.4045 degrees. Hence, the antenna array pattern improves the communication capacity largely. We see also in Fig. 3 that all the CDMA signals outside the chosen sector will be attenuated at least 0.5 attenuation coefficients. Hence, the interference signal from other users outside the chosen sector will be suppressed effectively by the linear antenna array as shown in Fig. 4. In Fig. 4, the antenna array of the BS can form 12 MIMO sub-sectors by one linear array antenna of the Triangle antenna array of Fig. 2. The Rake receivers in a MIMO sub-sector only process the multipath received signals of the given mobile users in the MIMO sub-sector. The spatial sub-sectors are obtained by the beamforming of the antenna array system we will discuss.

Remarks:

1. Since the MIMO sub-sectors in Fig. 4 have some width in spatial domain, the BS can assign some users in one sub-sector. The users for BS and the sub-sectors can be regarded as a MIMO system. In the MIMO system, BS needs not to consider the users' SSVs, only solves the multipath problem by presented 1-D Rake.
2. We also notice that the odd sub-sectors are nearly orthogonal each other, so are even sub-sectors, which means that the users in different odd sub-sectors can share the same CDMA channel, i..e. the same spreading code, so can the users in different even sub-sectors. The nearly orthogonal sub-sectors can obtain the spatial capacity of MIMO systems, following analysis and simulation will verify it.
3. The presented TD-SCDMA protocol[4] allotted a beam to one user, so it can only support 48 users whole cell, not obtain the spatial capacity by muti-beamforming. In fact, if a CDMA cell has 48 users per one carrier, it is not necessary to adopt such complicated technique-smart antenna for BS.

The remarks show the main difference of the paper to other presented papers about ST Rake[6]~[11].

The linear antenna array (1) forms a spatial filtering to received CDMA signals, the array pattern of the antenna is as following

$$|H(\theta)| = \left| \frac{\sin \frac{\pi d \sin\theta}{\lambda} N}{N \sin \frac{\pi d \sin\theta}{\lambda}} \right| \tag{3}$$

Considering the complexity of the array antennas, N should not be selected too large. In this paper, we adopt the linear array (1) with N=8 in every sector, and the interval of the antenna $d=\lambda/2$, then the array response $|H(\theta)|$ in Eq. (2) can be obtain as shown in Fig. 3. For our case of the linear array antenna with 8 elements, $H(\theta)$ divides the users in a sub-sector of a cell into 3 MIMO groups.

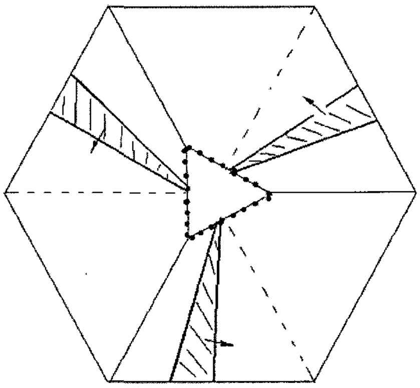

Fig. 2. Simplified antenna array structure.

The first MIMO group of mobile users is in

$|\theta_0| \leq 10^\circ \quad (\theta=\theta_0)$,

and it is of G_k users; the second MIMO group mobile users is in

$10^\circ < |\theta_1| \leq 18^\circ \quad (\theta=\theta_1)$,

it is of G_k^* users, the third MIMO group is in

$18^\circ < |\theta_2| \leq 120^\circ \quad (\theta=\theta_2)$,

it is of $K-G_k-G_k^*$ users.

Eq. (3) and Fig. 3 mean that all the CDMA signals to be outside of the given MIMO sector will be attenuated at least 0.5. Since the number of users to be outside of the given MIMO sector is far more than the

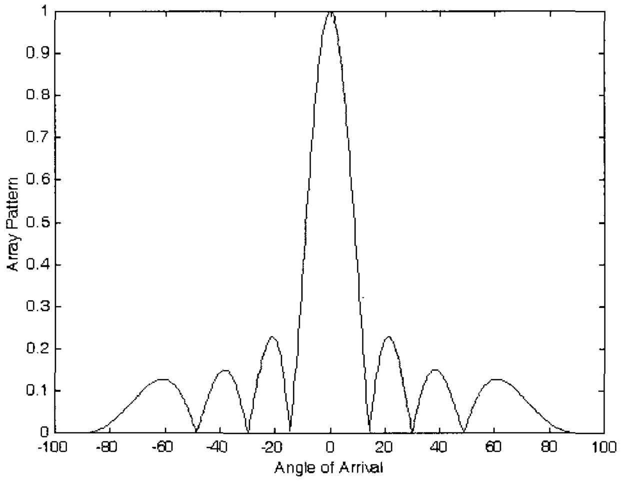

Fig. 3. The array pattern of the linear antenna array with 8 elements.

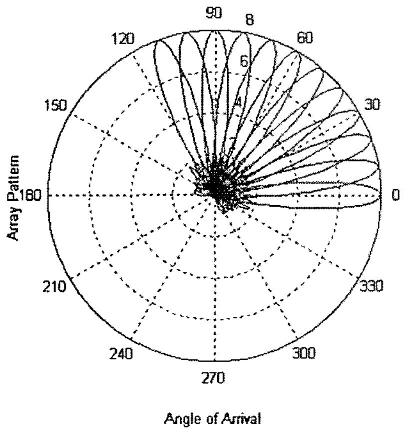

Fig. 4. MIMO subsector in 120° sector of BS.

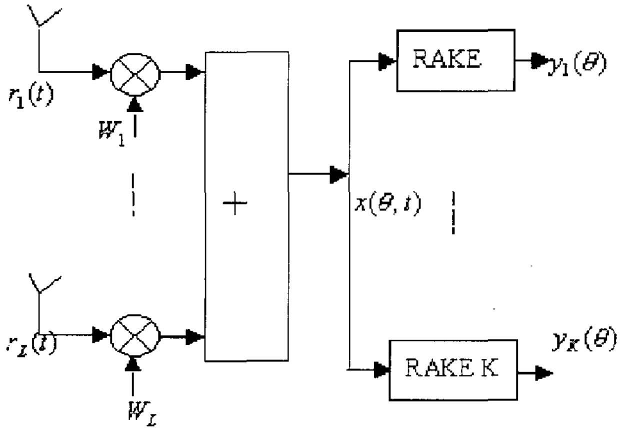

Fig. 5. Space-Time Rake receiver.

number of inside of the sector, the multi-assess interference can be cancelled effectively by array antenna.

However, according to Eq. (3) and Fig. 4, to divide the main sectors of a cell further we need 12 sets weights of array antennas for the 12 MIMO sub-sectors, shown in Fig. 4, which brings the hardware complexity of the CDMA system obviously.

To solve the problem, we use phase controlled linear array, for which each output of a sensor of the array will be multiplied a complex weight,

$$W_m(t)=e^{-j\frac{2\pi dm\sin\beta(t)}{\lambda}}. \tag{4}$$

The array antenna can produce a spatial signature vector(SSV) for a mobile in a TD-SCDMA cell

$$a(\theta,t)=[W_1(t),\ W_2(t)e^{j\frac{2\pi l\sin\theta}{\lambda}},\ldots,W_N(t)e^{j\frac{2\pi l(N-1)\sin\theta}{\lambda}}]^T \tag{5}$$

then we get the controlled array pattern of the antenna is as following

$$|H[\theta-\beta(t)]|=\left|\frac{\sin\frac{\pi d[\theta-\beta(t)]}{\lambda}N}{N\sin\frac{\pi d\sin[\theta-\beta(t)]}{\lambda}}\right| \tag{6}$$

When the DOA of a mobile user consists with $\beta(t)$, the beamforming direction of the linear array, the output of the linear array will be maximal.

From Eq. (5) and (6) we can see, when switching the complex weight $W_i(t)$ of the linear array periodically, at $t=t_1,\ldots,t_i,\ldots,t_N$, and $t_i\in[\underline{t_i},\overline{t_i}]$ the base station can form many sub-sectors from $-60°$ to $60°$ in a sector at different time intervals.

Because TD-SCDMA systems used Time Division technique [4], it is possible to switch the complex weight $W_i(t)$ of the linear array periodically[1],[3],[5].

III. Space-Time Rake Receivers

In the space-time Rake receivers, the transmitting signal from the mobile station that uses the k-th spreading code can be written by

$$s_k(t)=\sqrt{P_k}c_k(t)b_k,\quad 0\le t\le T_b \text{ and } k=1,\cdots,K \tag{7}$$

where $\sqrt{P_k}$, b_k and T_b, denote the signal amplitude, information symbol and the symbol period, respectively.

In Eq. (6), $c_k[t]$ is the k-th signaling waveform that is written as

$$c_k(t)=\sum_{n=0}^{M-1}c_k(n)p(t-nT_c)\ \text{for}\ 0\le t\le T_b \tag{8}$$

where M is the processing gain. $c_k(n)$ is the spreading code for the k-th CDMA channel, and $p(t)$ is a chip waveform of duration $T_c=T_b/M$.

The PN codes of the matched filters MF(i), i=1, $\cdots$, K, are of the following properties:

$$\int_0^{T_b}c_k(t)c_k(t)\,dt=T_b \tag{9a}$$

$$\int_0^{T_b}c_k(t)c_m(t)\,dt=\rho_{k,m}T_b \tag{9b}$$

and

$$\frac{1}{T_b}\int_{nT_b}^{(n+1)T_b}n(t)c_k(t)\,dt=n_k \tag{9c}$$

where $\rho_{m,k}$ (normalized) is the cross-correlation coefficient between the l-th and k-th CDMA waveform signatures.

We assume that the signals are synchronized, the received signal at the input of the first element of array antenna of the base station can be written as

$$r_1(t)=\sum_{m=1}^{N}\sum_{k=1}^{K}P_k c_k(t-\tau_{k,m})\alpha_{k,m}b_k+n(t) \tag{10}$$

and

$$r_m(t)=r_1(t)e^{j\frac{2\pi lm\ \sin\ \beta(t)}{\lambda}},\quad m=2,3,\cdots N \tag{11}$$

where b_k denotes the data symbol of the k-th user, $n(t)$ is the additive complex Gaussian thermal noise at the antennas and it is assumed to be temporally and spatially white.

The factor $\alpha_{k,m}$ in Eq. (10) denotes the channel attenuation of the k-th mobile to m-th element of the array antenna. In general, $\alpha_{k,m}$ can be considered as a random variable.

From Eq. (9), we can construct an input vector of the array antenna

$$\boldsymbol{r}(t)=[r_1(t),\ldots,r_L(t)]^T \tag{12}$$

The vector multiplies $\boldsymbol{a}(\theta,t)$ in Eq. (5), we realize the special filtering for given direction θ

$$x(\theta,t)=\boldsymbol{a}^T(\theta,t)\,\boldsymbol{r}(t). \tag{13}$$

From Eq. (8) and Eq. (13), we can get the outputs of the Rake Receivers of the TD-SCDMA systems for the k-th CDMA channel

$$\begin{aligned} y_k(\theta)&=\frac{1}{T_bN}\sum_{i=1}^{L}\int_{nT_b}^{(n+1)T)_b}x(\theta,t)c_k(t-\tau_{k,i})dt\\ &=x_k(\theta)+q_k(\theta),\quad k=1,2,\ldots,K \end{aligned} \tag{14}$$

where $\tau_{k,l}$ denotes time delay introduced by the l-path for $1\le l\le L$, with L denoting the number of resolvable paths,

$$x_k(\theta)=P_kH_k(\theta)\overline{\alpha_k}b_k \tag{15}$$

where

$$\overline{\alpha_k}=\frac{1}{N}\sum_{m=1}^{N}\alpha_{k,m} \tag{16}$$

and

$$q_k(\theta)=\sum_{\substack{m=1\\ m\neq k}}^{N}P_k\rho_{k,m}H_m(\theta)\alpha_{k,m}b_m+n_k. \tag{17}$$

The above algorithms Eq. (13) and Eq. (14) can be realized by the Space-Time Rake receiver shown in Fig. 5. The ST Rake receiver in Fig. 5 is different from those of [6]~[11], here we divide the ST Rake receiver into two parts: 1-D beamformer in space domain based on Eq. (13) and 1-D Rake receivers in time domain based Eq. (14).

In Fig. 5, The spatial beamformer filters the users in given direction, then Rake receivers detect the users' signals. The Rake receivers in Fig. 5 can be implemented by ones such as [12], i.e. the Rake block in Fig. 1.

From Eq. (2) and Fig. 3, the $H_k(\theta)$ in Eq. (15) and Eq. (17) is determined as follows

$$H_k(\theta)\approx\begin{cases}[0.5,1], & \text{if } |\theta|\le 10^\circ\\ [0.2,0.5], & \text{if } 10^\circ<|\theta|\le 15^\circ\\ [0.5,1], & \text{if} |\theta|>15^\circ\end{cases} \tag{18}$$

The interference of users is mainly from the users in the sector ($|\theta|\le 10^\circ$) the neighborhood ($10^\circ<|\theta|\le 15^\circ$) of the sector, for which, we need to apply Eq. (18), when we calculate the interference power. The interference of the other users will be attenuated to be less than 0.2 of the original ones. The results will be used to the computation of SINR and BER in following section. From Eq. (17), we can define w_k as the sum of interference vectors from other CDMA channels and the noise.

Consider the coherent uplink detection for the QPSK symbol b_k, the QPSK symbols can be detected as

$$\hat{b}_k=sign(y_k(\theta)/P_k) \tag{19}$$

where $sign(\cdot)$ is the complex sign function that is defined as

$$Re[sign(x)]=\begin{cases}\frac{1}{\sqrt{2}}, & \text{if } Re(x)>0\\ \frac{-1}{\sqrt{2}}, & \text{if } Re(x)\le 0\end{cases} \tag{20a}$$

and

$$Im[sign(x)]=\begin{cases}\frac{1}{\sqrt{2}}, & \text{if } Im(x)>0\\ \frac{-1}{\sqrt{2}}, & \text{if } Im(x)\le 0\end{cases} \tag{20b}$$

Eq. (19) provides the method to restore the user's signals from received signals, it can be programmed as a part of the receiver software of CDMA systems.

Ⅳ. Spatial Weights Calculation

The theoretical foundation of this weight eigenvalue algorithm for array antenna is MUSIC algorithm. MUSIC algorithm, namely Multiple Signal Classification, it utilizes the characteristic of orthogonal between the signal vector and noise vector and estimates the signal's direction of arrival(DOA) from the sub-space of signal[9]. The subspace of signal for the antenna array consists of two parts, the correlation metrics generated by the message source and noise source respectively. On the assumption that the power of useful signal is much greater than that of noise, we can calculate out the eigenvector of correlation matrix, and this eigenvector is correspond to the largest eigenvalue. After standardizing of the eigenvector with a weight factor, we can get the estimation about the DOA of desired user's signal. So we can design a spatial filter according to the above results and demodulate the received data that have been processed by the spatial filter.

The method for generating the weights' of array antenna is to analyze the correlation matrix of received signal $\boldsymbol{r}(t)$, given by Eq. (10)~Eq. (12). The autocorrelation matrix of $r(t)$ may be defined as:

$$\boldsymbol{R}_r = E[\,\boldsymbol{r}^T(t)\ \boldsymbol{r}(t)] = p_k^2 N^2 \boldsymbol{S} + \boldsymbol{Q} \qquad (21)$$

where $S = \overline{\alpha_1^2}\alpha(\theta_1)\alpha(\theta_1)^H$ denotes the term of signal matrix, $\boldsymbol{Q}$ represents the interference and noise terms

$$\boldsymbol{Q} = \sum_{k=2}^{K} \overline{\alpha_k^2} P_k^2 E[\overline{\rho_k^2}]\ \boldsymbol{a}^H(\theta_k)\,\boldsymbol{a}(\theta_k) + L\sigma^2 \boldsymbol{I} \qquad (22)$$

$$\overline{\alpha}_k = \sum_{m=1}^{L} \overline{\alpha}_{k,m}, \quad \overline{\rho}_k = \sum_{m=1}^{L} \overline{\rho}_{k,m} \text{ and } \sigma^2 = E[n^2(t)].$$

The explication about estimation of spatial filter can be seen below.

The Matrix $\boldsymbol{R}_r$ consists of the signal matrix N^2S and the full rank interference noise matrix $\boldsymbol{Q}$. The eigenvector $\hat{\boldsymbol{u}}_1$, corresponding to the largest eigenvalue of matrix $\boldsymbol{R}_r$, is a normalization vector. When the interference signals are wholly unrelative to the useful signal, the sole eigenvector is the linear sum of all channel vectors, so we can make a restriction that

$$\boldsymbol{W}^H\ \boldsymbol{W} = \frac{1}{N}$$

N is the size of the channel vector. Base on this condition, the weight vector may defined as

$$\hat{\boldsymbol{W}} = \frac{1}{\sqrt{N}}\ \hat{\boldsymbol{u}}_1 \qquad (23)$$

Here, $\hat{\boldsymbol{W}}$ is just the coefficients' vector of the spatial filter (5).

The process of algorithm to calculate the $\hat{\boldsymbol{W}}$ can be seen below:

Step 1: Calculate the correlation matrix $\boldsymbol{R}_r$ of $\boldsymbol{r}(t)$;

Step 2: decompose the correlation matrix $\boldsymbol{R}_r$ to pick out a series of eigenvalue $\{\lambda_1 \geq \lambda_2 \geq\ ,\dots\ , \lambda_N\}$,

Step 3: look for the solution of normal eigenvector $\hat{\boldsymbol{u}}_1$ corresponding to the largest one λ_1.

We can use Eq. (23) to calculate $\hat{\boldsymbol{W}}$, the coefficients of the spatial filter (5).

V. Properties of the Space-Time Rake Receivers

Because ST Rake involves beamformer and Rake, we need two steps to analyze the properties of the proposed ST Rake. First, consider the beamformer' algorithm in spatial domain. From Eq. (17) we have

$$R_{q_k} = E[q_k^2] = \sum_{m \neq k} E[\rho_{k,m}^2]\ E[P_k \alpha_{k,m}^2 H_k^2(\theta)] + \sigma^2 \qquad (24)$$

For our case of the linear array antenna with 8 elements, $H_k(\theta)$ divided the users in a sub-sector of a cell into 3 groups. The first group is in $|\theta_0| \leq 10°\ (\theta = \theta_0)$, and it is of G_k users; the second group is in

$10° \leq |\theta_1| \leq 18°\ (\theta = \theta_1)$,

it is of G_k^* users, the third group is in

$10° < |\theta_1| \leq 18°\ (\theta = \theta_1)$,

it is of G_k^* users, the third group is in

$18° < |\theta_1| \leq 120°\ (\theta = \theta_2)$,

it is of $K - G_k - G_k^*$ users.

Using power control in the CDMA system only in the sector, $E(P_k|\alpha_{k,m}|^2) \cong P_a$, $|\theta_1| \leq 10°$.

The covariance matrix R_{W_k} can be written as

$$R_{w_k} \leq H_k^2(\theta_0)(G_k - 1)P_a\overline{\rho^2} + H_k^2(\theta_1)G_k^* P_a\overline{\rho^2}$$
$$+ H_k^2(\theta_2)(K - G_k - G_k^*)P_a\overline{\rho^2} + \sigma^2 \qquad (25)$$

where the attenuation factors

$$H_k^2(\theta_0) = 1 \qquad (26a)$$

$$H_k^2(\theta_1) = 0.25 \qquad (26b)$$

$$H_k^2(\theta_2) = 0.04 \qquad (26c)$$

which are calculated by Eq. (18).

Though main interference comes from the users in the second term of Eq. (25), the number of the users belong to the domain is not large since the users are uniformly distributed generally. The third term of Eq. (25) reflects the interference of the users outside of the sector.

From Eq. (15) we have

$$R_{x_k} = E(x_k]^2 = NP_k|\overline{\alpha_k}|^2 \qquad (27)$$

When $u_k > 0$ and SSVs of the CDMA signals are orthogonal in spatial domain, from Eq. (25) and Eq. (27) we can get the $SINR_k$(SINR-Signal Interference Noise Ratio) for the k-th mobile user as following

$$SINR_k \cong NP_k|\overline{\alpha_k}|^2/[H_k^2(\theta_1)(G_k - 1)P_a\overline{\rho^2} + H_k^2(\theta_1)G_k^* P_a\overline{\rho^2}$$
$$+ H_k^2(\theta_2)(K - G_k - G_k^*)P_a\overline{\rho^2} + \sigma^2] \qquad (28)$$

It's obviously that $SINR_k$ is independent of the SSV of the k-th user. The flat fading channel indicates that $|\alpha_k|$ is Rayleigh-distributed. Under the power control

$$P_k E[|\overline{\alpha_k}|^2] = P_k \overline{\alpha^2} = P_\alpha = 1 \tag{29}$$

and substitute Eq. (29) into Eq. (25), we can get

$$\overline{SINR_k} \cong N/[H_k^2(\theta_1)(G_k-1)\overline{\rho^2} + H_k^2(\theta_1)G_k^*\overline{\rho^2} + H_k^2(\theta_2)(K-G_k-G_k^*)\overline{\rho^2} + \sigma^2] \tag{30}$$

Under the Gaussian approximation, the bit error rate (BER) can be written with the $\overline{SINR_k}$ as

$$\overline{BER_k} = Q(\sqrt{\overline{SINR_k}}) \tag{31}$$

where $Q(\cdot)$ is Gaussian approximation function. Using following formula, we also can get the average bit error rate:

$$\overline{BER_k} = \frac{1}{2}\left(1 - \sqrt{\frac{\overline{SINR_k}}{2+\overline{SINR_k}}}\right) \tag{32}$$

To compare the effect of array antenna, the $\overline{SINR_k}$ for the CDMA systems without array antenna can be derived from Eq. (30).

$$\overline{SINR_{k,NA}} = \frac{N}{(K-1)\overline{\rho^2} + \sigma^2} \tag{33}$$

Substituting Eq. (33) into Eq. (32), we can obtain $\overline{BER_k}$ of the CDMA systems without array antenna.

$$\overline{BER_{k,NA}} = \frac{1}{2}\left(1 - \sqrt{\frac{\overline{SINR_{k,NA}}}{2+\overline{SINR_{k,NA}}}}\right) \tag{34}$$

In Eq (30), $\overline{SINR_k}$ denotes the average attainable SINR(AA-SINR). It's independent of SSVs of users. In order to get higher $\overline{SINR_k}$, it's necessary to apply Rake in every sub-sectors, and Eq. (24)~Eq. (33) have not considered the Rake's time processing for the multipath CDMA signals.

Now, we consider the Rake effect in time domain. Section 2 and Section 3 reveal that the proposed ST Rake in fact is a combination of two 1-D processing systems: 1-D beamformer and presented 1-D Rake. Thus, we need not develop new $\overline{SINR_k}$ and $\overline{BER_k}$ formula for 1-D Rake, we only apply the known results[12] for each sub-sector, which is equal to a cell for classical Rake analysis. We have

$$\overline{SINR_{k,Rake}} \approx \frac{D_k^2}{2VAR[N_{noise}|\{\alpha_{k,i};\theta_{k,i}\}]} + \overline{SINR_k} \tag{35}$$

where $\overline{SINR_k}$ is given in Eq. (30), D_k^2 and $VAR[N_{noise}|\{\alpha_{k,i};\theta_{k,i}\}]$ are given by [12]. Substitute Eq. (35) into Eq. (31), we further get

$$\overline{BER_{k,Rake}} = Q(\sqrt{\overline{SINR_{k,Rake}}}) \tag{36}$$

Different from [12], when applying Eq. (35) and Eq. (36), the number of users is that of the given sub-sector, other conditions should not change.

Ⅵ. Simulations

In the simulation, we consider the joint multiuser detection with N=8, the number of sensors of linear antenna array, and K=31, the processing gain. The spreading codes are the Gold sequences, $\rho_{i,k} = -1/31$. We assume that the DOAs of the signals from Ks=600 mobile stations are uniformly distributed in a cell, then the number in a MIMO sub-sector such as $[-10°, 10°]$ should be $G_k = 33$, the number in the neighborhood of the sector such as $[-15°, -10°]$ and $[-15°, -10°]$ should be $G_k^* = 17$.

For a random spreading code assignment, the users can be of their spreading codes randomly. We assume the Rayleigh-distributed channels and the phase and DOAs are correctly known. Moreover, the uniform linear array(ULA) with the half wavelength spacing is used for the antenna array of the base station, i.e. $d=\lambda/2$. The antenna element number N=8 with the array pattern shown as in Fig. 3. Assume that $|\alpha_k|$ is Rayleigh-distributed and

$$E[|\alpha_k|^2] = 1, \quad P_\alpha = 1.$$

Substitute all the parameters into Eq. (26) and Eq. (27), we can get SINR curves shown in Fig. 6 and BER curves shown in Fig. 6. In the figures,

$$2E_b/N_0 = 1/\sigma^2.$$

The SINR curve and BER curve calculated by Eq. (30)~Eq. (33) are shown in Fig. 6 and shown in Fig. 7, respectively.

In Fig. 6, the upper SINR curve denotes proposed ST Rake TD-SCDMA system, the middle SINR curve denotes presented TD-SCDMA system without ST Rake only using beamformers, the lower SINR curve denoted the classical CDMA system without ST Rake. Compared with the latter two CDMA systems, the proposed ST Rake CDMA systems obtained much higher SINR under the condition of enlarging capacity of CDMA systems, with 600 users. Original design[4] for TD-SCDMA can support 48 users per carrier only.

Similarly, in Fig. 7, the lower BER curve denotes proposed ST Rake TD-SCDMA system, the middle BER curve denotes presented TD-SCDMA system without ST Rake only using beamformers, the upper BER curve denoted the classical CDMA system without ST Rake. Compared with the latter two CDMA systems, the

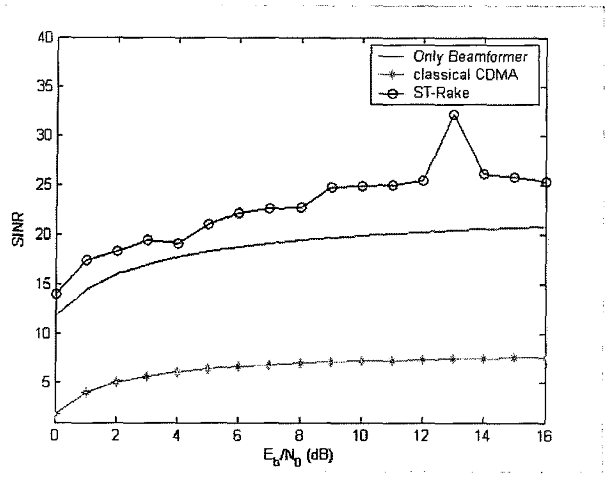

Fig. 6. SNIR curves versus E_b/N_0.

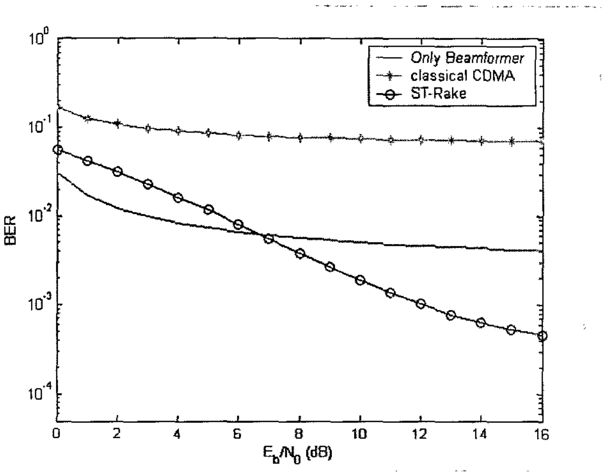

Fig. 7. BER curves versus E_b/N_0.

proposed ST Rake CDMA systems also obtain much lower BER, under the condition of user capacity of 600 users.

The presented other papers have not consider the problem of users capacity with multi-beamforming when design their ST Rake receivers, while this paper explored the possibility of enlarging user capacity by ST Rake and keeping the communication quality. However, managing and switching MIMO sub-sectors are still complex, need to be studied further.

VII. Conclusion

In this paper, we present an algorithm of space-time Rake receivers that are based on the MIMO information of the CDMA mobile signals. This paper revised the presented TD-SCDMA BS design, to simplify the implementation of ST Rake as well as enlarge the system capacity. The ST Rake of the paper can be realized by 1-D spatial beamformers and 1-D Rake receivers, which can reduce the BS complexity greatly, the diagram block of proposed TD-SCDMA base station has been provided. Different from the presented ST Rake schemes, this paper allows one beam to be shared many CDMA users to increase the system capacity, and develops the MIMO sub-sectors, which are constructed by nearly orthogonal multi-beamforming of BS. The theory analysis and simulations show that the proposed ST Rake receivers are effective, and they can ensure good BER and SINR performances under the complicated condition of many mobile users in a MIMO sub-sector when a cell is divided into many MIMO sub-sectors by the proposed beamforming.

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References

[1] Y. Xiao, L. Lu, and J. Habermann, "Dynamic spatial CDMA channel assignments for TD-SCDMA systems", *Proceedings of the IEEE Conference on Decision and Control*, vol. 1, pp. 1104-1109, 2003.

[2] Y. Xiao, L. Lu, and S. Hu, "Downlink multi-beamforming control for the smart antennas of TD-SCDMA base stations", *Proceedings of 2004 7th International Conference on Signal Processing Proceedings(ICSP'04)*, vol. 1, pp. 451-454, 2004.

[3] Y. Xiao, L. Lu, and J. Habermann, "Communication capacity of TD-SCDMA systems", *Proceedings of International Conference on Communication Technology*, vol. 2, pp. 1185-1189, 2003.

[4] Working Group 1(WG1), China Wireless Telecommunication Standard(CWTS): TS C105 V3.0.0, Oct. 1999.

[5] Y. Xiao, J. Habermann, W. Yao, and H. Han, "Time-switching space-time multiuser detection for CDMA systems", *Proceedings of IEEE Region 10 Annual International Conference(TENCON'02)*, vol. 2, pp. 1117-1121, 2002.

[6] J. Ramos, M. D. Zoltowski, and H. Liu, "A low-complexity space-time Rake receiver for DS-CDMA communications", *IEEE Signal Processing Letters*, vol. 4, no. 9, pp. 262-265, 1997.

[7] Y. Chen, M. D. Zoltowski, J. Ramos, C. Chatterjee,

and V. P. Roychowdhury, "Reduced-dimension blind space-time 2-D Rake receivers for DS-CDMA communication systems", *IEEE Trans, Signal Processing*, vol. 48, no. 6, pp. 1521-1536, 2000.

[8] H. Boche, M. Schubert, "Space-time rake reiver with optimal beamforming for the uplink of CDMA-based wireless systems", *Proceedings of IEEE International Symposium on Circuits and Systems*, 2000, III-109-III-112.

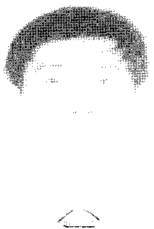
[9] W. Wang, B. Jiang, and Qinye Yin, "A beam tracking algorithm for space-time Rake receiver with a new beamformer", *Proceedings of IEEE International Symposium on Circuits and Systems (ISCAS'00), Geneva*, vol. 4, pp. 613-616, 2000.

[10] T. Lee, T. Tsai, "A beamspace-time Rake receiver for sectored CDMA systems", *Proceedings of 2000 IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP'00)*, vol. 5, pp.2849-2852, 2000.

[11] C. Brunner, M. Haardt, and J. A. Nossek, "On space-time Rake receiver structures for WCDMA", *Proceedings of The Thirty-Third Asilomar Conference on Signals, Systems, and Computers*, vol. 2, pp. 1546-1551, 1999.

[12] W. Yao, Y. Xiao, "A novel SIR weighting combining diversity method for mobile communication system", *Proceedings of International Conference on Communication Technology(ICCT'03)*, vol. 2, pp. 995-999, 2003.

Yang Xiao

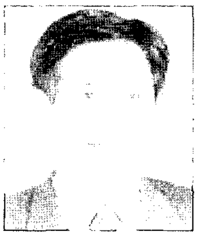


received the B.S. degree in Electronics Engineering from the Beijing University of Post and Telecommunication, China, in 1983, M.S. degree in Communication and Electronics Systems from the Beijing Jiaotong University, China, in 1989, Ph.D. degree in Signal Processing from the Beijing Jiaotong University, China, in 1991. Since 1991, He has been with Institute of Information Science, as lecture (1991-1993), associate professor (1993-2000) and professor (2000-now) Beijing Jiaotong University, Beijing, China. From 1996-1998, He was DAAD senior visiting scientist and DFG senior visiting scientist with University of Erlangen Nuremnberg, Germerny. In 2002, he was DAAD senior visiting scientist with Applying Science University of Friedberg-Giessen, Germerny. From 2005-2006, he was Brain Pool visiting professor with the Institute of Information and Communication, Chonbuk National University, Korea. His research interests include the areas of mobile communications, queuing theory, MIMO systems, space-time processing, multi-dimensional(M-D) systems' theory and M-D signal processing.

Kwang-Jae Lee

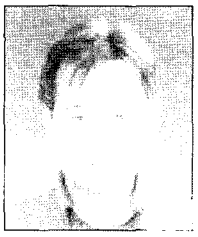
received the B.S. and M.S. degrees in electronic engineering from Chonbuk National University in 1986, 1990 respectively. He is currently a full time lecturer in Hanlyo University. His research interests include the areas of mobile communications, RFID, powerline communications, and channel coding.

Moon-Ho Lee



received the B.S. and M.S. degrees both in Electrical Engineering from the Chonbuk National University, Korea, in 1967 and 1976, respectively, and the Ph.D. degree in electronics engineering from the Chonnam National University in 1984 and the University of Tokyo, Japan, in 1990. From 1970 to 1980, he was a chief engineer with Namyang Moonhwa Broadcasting. Since 1980, he has been a professor with the Department of Information and Communication and a Director with the Institute of Information and Communication, both at Chonbuk National University. From 1985 to 1986, he was also with the University of Minnesota, as a Postdoctoral Feller. He has held visiting positions with the University of Hannover, Germany, during 1990, the University of Aachen, Germany, during 1992 and 1996, and the University of Munich, Germany, during 1998. His research interests include the multidimensional source and channel coding, mobile communication, and image processing.

Sam-Goo Cho



received the B.S. degree in electronic engineering from Hankuk Aviation University in 1989. He is currently a Senior Research Engineer in SoC Center of Korean Electronics Technology Insti- tute. His research interests include the areas of analog/digital hybrid signal processing IC.