A Novel Smart 2-Dimensional RAKE Receiver

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Abstract — RAKE receiver is widely used in wideband code division multiple access (W-CDMA) system to combat the multipath fading. RAKE receiver can co-phase the multipaths signals and add these signals to form the coherent output. Combined the spatial with temporal diversity features, RAKE receiver can be generalized into two dimensional and is expected to have further performance improvement when the channel estimation is perfect. In this paper, we will propose an analytical smart two dimensional RAKE receiver to choose the receiving antenna number and finger number dynamically under imperfect channel estimation. Experimental measured examples are presented to analyze the performance improvement of the proposed method.

Key Words — W-CDMA, RAKE, LOS, NLOS

I. INTRODUCTION

In a W-CDMA system, receiving site uses the RAKE receiver to increase the signal to interference noise ratio (SINR). The conventional architecture of a RAKE receiver can be shown in Fig.1. The received signal is delayed and multiplied a complex coefficient to form the coherent output of the receiver. Furthermore, RAKE receiver can be generalized into two-dimensional (2D), i.e., one in the spatial domain and the other in the temporal domain. A $M$ antennas $P$ fingers 2D RAKE receiver can be depicted in Fig.2. In this figure, $r_{i,j,0}$ is the time delay of the $ith$ multipath for the $jth$ antenna of the desired user, $w_{i,j,0}^*$ is the properly selected coefficient to co-phase the received signal. In the spatial domain, a 2D RAKE receiver uses multiple antennas to increase system performance, many methods such as multiple inputs multiple outputs (MIMO) scheme or smart antenna can be applied in spatial domain. For the temporal domain, RAKE receiver uses multiple fingers to increase signal strength. The adopted fingers can retrieve desired signal from the multipaths channel. If the time difference of two incident multipaths signals is greater than a chip time, RAKE receiver can co-phase the multipaths signals to improve system performance. Therefore, multipaths channel will be a constructive effect instead of a troublesome problem.

Theoretically, SINR will be increased as the adopted antenna number ($M$) and RAKE finger number ($P$) increase [8]. However, this statement is true only when the channel can be perfectly estimated. However, in all practical situations, channel attenuation can not be perfectly estimated. In a W-CDMA system, channel estimation errors come mainly from the multiple access interference (MAI) and Additive White Gaussian Noise (AWGN).

Fig.1 Architecture of a RAKE Receiver

Fig.2 A 2D RAKE Receiver

In the literatures, most researches focused on studying the performance of RAKE receiver with perfect channel estimation [2-5]. In [6], experimental results of RAKE finger life distance were presented. It illustrates the nature of the variations of the contributive RAKE fingers under different channel scenarios. In [7], a dynamic RAKE finger number method was proposed. It uses the numerical and experimental results to give a set of suggested parameters, such as path-selection set level, delay profile averaging time, etc. Nevertheless, the proposed method considers only in the temporal domain. In this paper, we will propose a smart 2D RAKE receiver that can choose its spatial antenna number ($M$) and temporal finger number ($P$) properly according to the variation of the wireless channel between transmitter and receiver. We use the output SINR of a 2D RAKE receiver as an indicator to analyze the performance.
improvement of the proposed method. This paper is organized as followed; we will statistical derive the method of smart 2D RAKE receiver in Section II. The results are derived under the imperfect channel estimation scenario and are compared with the perfect estimation case. Experimental results are given in Section III to demonstrate the effectiveness of the propose method. Conclusions on this paper will be given in Section IV.

II. DERIVATIVES OF THE PROPOSED SMART 2D RAKE RECEIVER

In W-CDMA system, if a 2D RAKE receiver adopts $M$ antennas for receiving, a $P$-paths time-invariant channel for the $k$th user at the $m$th receiving antenna can be modeled as

$$h_{m,k}(t) = \sum_{p=0}^{P-1} h_{p,m,k}(t - \tau_{p,m,k})$$

(1)

where $h_{p,m,k}$ is the attenuation at time $\tau_{p,m,k}$. $\tau_{p,m,k}$ is the time-of-arrival (TOA) of the $p$th multipath at the $m$th receiving antenna for the $k$th user. $\delta(t)$ is the delta function.

Let the dedicated physical control channel (DPCCH) and the dedicated physical data channel (DPDCH) of the desired user have the spreading factor $F_c$ and $F_d$ respectively. The $p$th finger output voltages $y_{c,p,m}$, $y_{d,p,m}$ of the matched filter (MF) for the DPCCH and DPDCH can be expressed as followed

$$y_{c,p,m} = F_c h_{p,m,0} + i_{c,p,m} + n_{c,p,m} = F_c h_{p,m,0} + \eta_{c,p,m}$$

(2)

$$y_{d,p,m} = b F_d h_{p,m,0} + i_{d,p,m} + n_{d,p,m} = b F_d h_{p,m,0} + \eta_{d,p,m}$$

(3)

where $h_{p,m,0}$ is the $p$th multipath attenuation for the desired user, $i_{c,p,m} \sim i_{d,p,m}$ and $n_{c,p,m} \sim n_{d,p,m}$ are the $p$th MAI and AWGN of the DPCCH and DPDCH channel at the $m$th receiving antenna. $b = \pm 1$ is the randomly transmitted binary symbol. The statistical properties of these random variables are

$$E[y_{c,p,m}^2] = F_c (K - 1)$$

$$E[p_{c,p,m}^2] = F_c \sigma_n^2$$

$$E[\eta_{c,p,m}^2] = E[y_{c,p,m}^2] = E[y_{d,p,m}^2] = F_c (K - 1) + \sigma_n^2$$

$$E[\eta_{d,p,m}^2] = F_d \sigma_n^2$$

$$E[y_{d,p,m}^2] = E[i_{d,p,m}^2] + E[n_{d,p,m}^2] = F_d (K - 1) + \sigma_n^2$$

(4)

where $K$ is the total number of users. $\sigma_n^2$ is the AWGN noise power, $E[\cdot]$ is the expectation operator.

In this paper, we use the maximum ratio combining (MRC) to combine the RAKE finger outputs. MRC multiplies the complex conjugate of the DPCCH channel estimation to maximize the output SINR in the DPDCH channel. Assume that the DPCCH and DPDCH have the same channel characteristics during transmission, the output voltage of the DPDCH channel $V_{\text{out}}$ of the 2D RAKE receiver is given by

$$V_{\text{out}} = \sum_{m=1}^{M} \sum_{p=1}^{P} y_{d,p,m} y_{c,p,m}^*$$

(6)

Suppose that the DPCCH can estimate the channel perfectly, i.e., free of MAI and AWGN ($\eta_{c,p,m} = \eta_{d,p,m} = 0$), we have the relation $y_{c,p,m} = F_c h_{p,m,0}$ from Equ.(2) and insert it into Equ.(6), $V_{\text{out}}$ can be expressed as

$$V_{\text{out}} = \sum_{m=1}^{M} \sum_{p=1}^{P} b F_d h_{p,m,0} + \eta_{d,p,m} F_c h_{p,m,0}^*$$

(7)

$$= b F_d \sum_{m=1}^{M} \sum_{p=1}^{P} h_{p,m,0}^2 + \sum_{m=1}^{M} \sum_{p=1}^{P} \eta_{d,p,m} F_c h_{p,m,0}^*$$

The SINR for the $P$-fingers $M$-antennas MRC RAKE receiver with perfect channel estimation at the DPDCH is

$$SINR_{\text{Perfect}}^P = \frac{\sum_{m=1}^{M} \sum_{p=1}^{P} h_{p,m,0}^2}{\sum_{m=1}^{M} \sum_{p=1}^{P} \eta_{d,p,m}^2}$$

(8)

$$= \frac{F_d^2 (K - 1) + \sigma_n^2}{(K - 1) + \sigma_n^2}$$

where we have assumed that $E[\eta_{d,p,m} \eta_{d,p,m}^*] = 0$ and $E[\eta_{d,p,m} \eta_{d,p,m}^*] = 0$ for $p \neq p'$ and $m \neq m'$. In this case, we can see that with the increase of $M$ and $P$, SINR will be increased. It consists with the theoretical prediction in [8].

Consider the case when the DPCCH cannot estimate the channel perfectly, i.e., $\eta_{c,p,m} = i_{c,p,m} + n_{c,p,m} \neq 0$, the output voltage $V_{\text{out}}$ of the DPDCH of 2D RAKE receiver is as Equ.(9). In Equ.(9), the first term is the signal part and the other terms come from the MAI and AWGN interferences. Therefore, the output SINR for the 2D RAKE receiver is given by Equ.(10) where we have assumed that $E[\eta_{d,p,m} \eta_{d,p,m}^*] = 0$ for $p \neq p'$, $m \neq m'$, $E[\eta_{c,p,m} \eta_{c,p,m}^*] = 0$ for $p \neq p'$, $m \neq m'$ and $E[\eta_{c,p,m} \eta_{c,p,m}^*] = 0$ for all $p, p', m, m'$. We established the relation between SINR and $M$, $P$ under the imperfect channel estimation scenario in Equ.(10).
\[
V_{\text{out}} = \sum_{m=1}^{M} \sum_{p=1}^{P} (b F_d h_{p,m,0} + \eta_{d,p,m}\bar{h}_{p,m,0} + \eta_{c,p,m}^*) \sum_{m=1}^{M} \sum_{p=1}^{P} h_{p,m,0}^* + \eta_{d,p,m}^* F_{c} h_{p,m,0}^* + \eta_{d,p,m} h_{c,p,m}^* \\
= b F_d F_c \sum_{m=1}^{M} \sum_{p=1}^{P} |h_{p,m,0}|^2 + b F_d \sum_{m=1}^{M} \sum_{p=1}^{P} h_{p,m,0}^* \bar{h}_{p,m,0}^* + \eta_{d,p,m}^* F_{c} h_{p,m,0}^* + \eta_{d,p,m} h_{c,p,m}^* \\
\]

\[
\text{SINR}_{\text{interference}}^{P,M} = \frac{F_d^2 F_c^2 \left( \sum_{m=1}^{M} \sum_{p=1}^{P} |h_{p,m,0}|^2 \right)^2}{E \left\{ b F_d \sum_{m=1}^{M} \sum_{p=1}^{P} h_{p,m,0}^* \bar{h}_{p,m,0}^* + \sum_{m=1}^{M} \sum_{p=1}^{P} \eta_{d,p,m} F_{c} h_{p,m,0}^* + \sum_{m=1}^{M} \sum_{p=1}^{P} \eta_{d,p,m} h_{c,p,m}^* \right\}^2} \\
= \frac{F_d^2 F_c^2 \left( \sum_{m=1}^{M} \sum_{p=1}^{P} |h_{p,m,0}|^2 \right)^2}{\left( K-1 + \sigma_n^2 \right) (F_d + F_c) \sum_{m=1}^{M} \sum_{p=1}^{P} |h_{p,m,0}|^2 + PM \left( K-1 + \sigma_n^2 \right)} \\
\]

\[
\text{SINR}_{\text{interference}}^{P=1, M} = \frac{F_d^2 F_c^2 \left( \sum_{m=1}^{M} \sum_{p=1}^{P} |h_{p,m,0}|^2 \right)^2}{E \left\{ b F_d \sum_{m=1}^{M} h_{p,m,0}^* \bar{h}_{p,m,0}^* + \sum_{m=1}^{M} \eta_{d,m} F_{c} h_{p,m,0}^* + \sum_{m=1}^{M} \eta_{d,m} h_{c,m}^* \right\}^2} \\
= \frac{F_d^2 F_c^2 \left( \sum_{m=1}^{M} \sum_{p=1}^{P} |h_{p,m,0}|^2 \right)^2}{\left( K-1 + \sigma_n^2 \right) (F_d + F_c) \sum_{m=1}^{M} \sum_{p=1}^{P} |h_{p,m,0}|^2 + M \left( K-1 + \sigma_n^2 \right)} \\
\]

\[
\text{SINR}_{\text{interference}}^{P,M=1} = \frac{F_d^2 F_c^2 \left( \sum_{p=1}^{P} |h_{p,1,0}|^2 \right)^2}{E \left\{ b F_d \sum_{p=1}^{P} h_{p,1,0}^* \bar{h}_{p,1,0}^* + \sum_{p=1}^{P} \eta_{d,p,1} F_{c} h_{p,1,0}^* + \sum_{p=1}^{P} \eta_{d,p,1} h_{c,p,1}^* \right\}^2} \\
= \frac{F_d^2 F_c^2 \left( \sum_{p=1}^{P} |h_{p,1,0}|^2 \right)^2}{\left( K-1 + \sigma_n^2 \right) (F_d + F_c) \sum_{p=1}^{P} |h_{p,1,0}|^2 + P \left( K-1 + \sigma_n^2 \right)} \\
\]

3
Compared with Equ.(8) which is the output SINR with perfect channel estimation, we can see that SINR will be degraded due to MAI and AWGN interferences. In a 2D RAKE receiver, we want to properly choose the number of \( M \) and \( P \) to have a better output SINR of the receiver.

In the case of spatial domain, we want to select the contributive antennas (or decide the antenna number \( M \)) to increase output SINR. The problem can be interpreted as to have the proper \( M \) when \( P = 1 \) in Equ.(10). This condition reduce Equ.(10) into Equ.(11).

\[
\begin{align*}
|\mathbf{H}_{M+1,0}|^2 &> \left|\mathbf{H}_{M,0}\right|^2 + \left|\mathbf{H}_{M+1,0}\right|^2 + 4\left|\mathbf{H}_{M,0}\right|\left|\mathbf{H}_{M+1,0}\right| - H_{M+1,0} \tag{11}
\end{align*}
\]

To decide whether the \((M+1)th\) antenna can be chosen or not. Based on the criterion \( SINR^{M+1} > SINR^M \), let \( |\mathbf{h}_{1,m,0}| \geq |\mathbf{h}_{1,m+1,0}|, m = 1,2,...M-1 \) in the descending order, insert Equ.(11) into this criterion, the added \((M+1)th\) antenna can increase system performance only when the following condition holds.

\[
\left|\mathbf{H}_{M+1,0}\right|^2 > \left|\mathbf{H}_{M,0}\right|^2 + \left|\mathbf{H}_{M+1,0}\right|^2 + 4\left|\mathbf{H}_{M,0}\right|\left|\mathbf{H}_{M+1,0}\right| - H_{M+1,0} \tag{11}
\]

where we have assumed that \( H' = \sum_{m=1}^{M} |\mathbf{h}_{m,0}|^2 \),

\[
B = \left[K-1 + \sigma_n^2\right] > 0 \quad \text{and} \quad E = F_d + F_e .
\]

Therefore, the added \((M+1)th\) antenna is contributive if the requirement of Equ.(12) is satisfied.

As for the temporal domain, consider the simple scenario where we have only one receiving antenna only. Equ.(10) reduces to Equ.(13) when \( M = 1 \).

Based on the criterion \( SINR^{P+1} > SINR^P \), let \( H = \sum_{p=1}^{P} |\mathbf{h}_{p,1,0}|^2 \), \( \left|\mathbf{h}_{p,1,0}\right| \geq \left|\mathbf{h}_{p+1,1,0}\right|, p = 1,2,...P-1 \) in the descending order, the added \((P+1)th\) finger can increase system performance (increase SINR) only when the following condition holds.

\[
\left|\mathbf{H}_{P+1,1,0}\right|^2 > \left|\mathbf{H}_{P,1,0}\right|^2 + \left|\mathbf{H}_{P+1,1,0}\right|^2 + 4\left|\mathbf{H}_{P,1,0}\right|\left|\mathbf{H}_{P+1,1,0}\right| - H_{P+1,1,0} \tag{14}
\]

That is, for a single antenna, the output SINR of the RAKE receiver can be increased with the added \((P+1)th\) finger if the requirement of Equ.(14) can be satisfied. On the contrary, if the added power delay profile of the \((P+1)th\) finger doesn’t satisfy Equ.(14), the added finger will have no contribution on the output SINR and can even decrease the SINR instead. Since Equ.(14) can be applied to any receiving antenna, such as the \( mth \) antenna, Equ.(14) can be generalized to Equ.(15) for the \( mth \) receiving antenna to properly decide its RAKE finger number.

\[
\left|\mathbf{H}_{m,1,0}\right|^2 > \left|\mathbf{H}_{m,0}\right|^2 + \left|\mathbf{H}_{m+1,0}\right|^2 + 4\left|\mathbf{H}_{m,0}\right|\left|\mathbf{H}_{m+1,0}\right| - H_{m} \tag{15}
\]

The operation of the proposed smart 2D RAKE receiver can be illustrated as followed:

1. Using Equ.(12) to select the antennas (antenna number \( M \)) suitable for receiving at some time instant. This operation can be illustrated in Fig.3.

2. Using Equ.(15) to decide the proper fingers (finger number \( P \)) for each antenna selected in above operation. This operation is illustrated in Fig.4.

3. Based on the antenna selected in operation (1) and the finger number decided in operation (2) for each antenna, a 2D RAKE receiver can decide the effective antennas and fingers to retrieve the desired signal. Fig.5 is an example if there are 4 antennas for the 2D RAKE, using the proposed method, the resulted 2D RAKE receiver can have the architecture of 3 receiving antennas, each with 2, 1, and 3 fingers respectively to have the best performance at some time instant. The \( mth \) antenna may not be selected if Equ.(12) is not satisfied.

4. Repeat operation (1) to (3) during signal transmission on each time slot. That is, change its receiving antennas and fingers dynamically to have the best system performance.

III. SIMULATION RESULTS

In this section, we use the measured channel state information (CSI) to see the performance of the proposed smart 2D RAKE receiver. We present the SINR improvement of the method compared with the traditional fixed fingers, fixed antennas 2D RAKE receiver. CSI was measured by using the RUSK channel sounder. We used one transmitting antennas and four receiving antennas to conduct this experiment. Spacing between two receiving antennas is \( \lambda \), \( \lambda \) is the wavelength and the carrier frequency is 2.44GHz. 5MHz bandwidth was measured to satisfy the W-CDMA requirement [1]. Fig. 6 shows the layout of the campus of National Taiwan University and the traveling paths of the mobile are shown. The receiver was placed on the top of an 11 floors building and was marked as Rx in the figure. Two wireless channel scenarios are evaluated in this simulation, one is the Line-of-Sight (LOS) case and the other is the NonLine-of-Sight (NLOS) case. 400 delay profiles were measured along each case for the statistical analysis. The synthesized MAI measurement scenario is as followed. The desired user is moving along Path-1 for the LOS case and Path-2 for the NLOS case. Other MAI interference sources are randomly distributed along Path-3, Path-4 and Path-5. Total number of interference sources is 10 and each delay profile is randomly selected from the measured delay profile on Path-3, Path-4 and Path-5. For simplicity, the spreading factors of the DPCCH and DPDCH (\( F_c, F_d \)) are set to 256 and 64 respectively for all users.

Fig. 7(a), Fig. 7(b) and Fig. 7(c) are the experimental results if we compare the proposed smart 2D RAKE
receiver with conventional fixed antennas (\( M = 1, M = 2, M = 4 \) respectively) and fixed fingers (\( P = 6, P = 10 \) ) 2D RAKE in the LOS case. The proposed method can vary its receiving antenna (from 1 to \( M \) ) and dynamically choose its appropriate spatial antennas and RAKE fingers according to the decision rule in Fig. 3 and Fig. 4. Results illustrate the cumulative distribution probability (CDF) of the measured SINR for the different architecture of 2D RAKE receiver along LOS path. We can see that the proposed method has the best performance results in these situations. Statistically, the proposed method has the 2-8dB SINR improvement in the mean sense. Besides, Fig. 8(a), Fig. 8(b) and Fig. 8(c) are the similar experimental results in the NLOS case. Statistically, it will have 2-4dB SINR improvement compared with the conventional methods. An interesting effect can be noted that the proposed method seems to have better performance improvement in the LOS case compared with the NLOS case. This can be interpreted as followed. In our experiences on channel measurement, most of the contribution of the desired signal comes mainly from 1-3 dominant paths in the LOS case. Actually, extra added fingers of the RAKE receiver will have no contribution on the total received signal strength except for signal contamination. Therefore, proper antenna and finger number of a 2D RAKE receiver should be carefully chosen to have satisfactory results.

IV. CONCLUSION

In this paper, we derive an analytic method to make the 2D RAKE receiver more smart and intelligent. We used the measured CSI to analyze the system degradation and to verify the effectiveness of the proposed dynamic method. Simulation results have shown that the proposed method outperform than the conventional fixed antenna and fixed finger 2D RAKE receiver under the imperfect channel estimation scenario. Since the proposed method is trivial and analytic, it can be implemented easily in the 3G W-CDMA system.

REFERENCE

Spreading Factor Number of User, Statistics of the Interference are Known at the Receiver

Estimate the Delay Profile of the Desired User $|\tilde{h}_{\text{des}}|$

Sort the Peak of the Delay Profile of the Desired User $|\tilde{h}_{\text{des}}|, |\tilde{h}_{\text{des}}|_P, P=1, 2, P-1$

$P=1$

$P=P+1$ \(\rightarrow\) \(\text{YES}\)

$satisfy\ Eq.\ (15)$

Choose the $P$ fingers RAKE Receiver for the Desired User

Fig. 4 The Dynamic Finger Number Decision Method for the Selected Antenna

Fig. 5 Example of the Proposed Dynamic Method (The 4th antenna is not selected at some time instant)
Fig. 7(c) Experiment Results in LOS case (M=4)

Fig. 8(a) Experiment Results in NLOS case (M=1)

Fig. 8(b) Experiment Results in NLOS case (M=2)

Fig. 8(c) Experiment Results in NLOS case (M=4)