PAPER

Multiple Pre-Rake Filtering Based on the Predicted Channel Impulse Response in the Transmitter and a Rake Combiner in the Receiver for TDD/DS-CDMA Mobile Communication Systems

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SUMMARY The pre-Rake system is known as a technique in TDD DS/CDMA system to reduce the mobile complexity and achieve the same BER performance like Rake receiver. The pre-Rake system itself is not optimum, since the channel impulse responses of uplink and downlink are slightly different in TDD system, so the signal- to-noise ratio (SNR) can be maximized with a matched filter based Rake receiver, which has not been considered in the conventional pre-Rake system. Furthermore pre-Rake system is sensitive to the Doppler frequency. Even though the pre-Rake system has the ability to suppress other user interference, it is not efficient to maximize the received signal in high Doppler frequency. However, Rake combiner is utilized for the detection method in our proposed system. So the maximized signal can keep the orthogonality better than the pre-Rake system and our proposed system can compensate the Doppler frequency effect. From these reasons, our system achieves better BER performance than that of the pre-Rake system with increasing the number of users in high Doppler frequency.
key words: *CDMA, Rake receiver, pre-Rake system, time division duplex (TDD)*

1. Introduction

Direct Sequence-Code Division Multiple Access (DS-CDMA) communication systems have recently attracted considerable attention as mobile cellular and IMT-2000 communication systems due to their ability to suppress a wide variety of interfering signals including narrow-band interference, multiple access interference (MAI), and multipath interference (MPI). In the presence of frequency selective fading, the capacity of the system can be enormously enlarged through multipath diversity gained by utilizing a Rake receiver structure [1], [2]. In mobile station, Rake receiver should be simple, so system performance is interior to that of the base station. Pre-Rake diversity system has been proposed for reducing complexity of mobile and the BER performance can be achieved to be equivalent to the Rake system of Base station [3], [4]. Recently, preprocessing techniques at the base station like pre-Rake and pre-equalization are widely studied for improving the downlink system performance [5], [6]. It is shown that the pre-Rake improves downlink system capacity in comparison to a Rake receiver [7]. Jeong and Ruly propose pre-Rake transmission diversity using multiple antennas to increase the system performance [8], [9]. Zazo compares the system performance of pre-Rake and that of Rake receiver with multi-user detection (MUD) [10]. The pre-Rake has variety merits for increasing the system performance, but the pre-Rake system is sensitive to the Doppler frequency effect. In the pre-Rake system, the signals considered as time reversed channel impulse response are transmitted and they arrive to the mobile station at the same time. It means that pre-Rake system uses the channel impulse response information only one time in order for the receiver to receive the transmitted signal at the same time without Rake receiver in the mobile station. However, it is sensitive to Doppler frequency effect in high Doppler frequency. The proposed system is to remunerate the sensitivity of pre-Rake system to Doppler frequency effect and maximize the SNR of the pre-Rake system. In multiuser case, the pre-Rake system achieves good channel capacity [7], but the performance is degraded by the high Doppler frequency. In this case, the pre-Rake and Rake combing can obtain better BER performance than that of the only pre-Rake system in high Doppler frequency, since the Rake receiver can remunerate the Doppler frequency effect. Moreover, the channel impulse responses of uplink and downlink are slightly different, so the performance of the TDD based pre-Rake system is interior to that of Rake system in low Doppler frequency [4]. In this case, Rake receiver also can maximize the received signal by using the conjugate term of slightly different channel response. When we use pre-Rake filter in the transmitter, and Rake combiner with whole path fingers in the receiver, the weak paths tend to degrade slightly the average BER performance since the accuracy of channel estimation tends to deteriorate on the low power peaks. It means that one pre-Rake filter in the transmitter and Rake combiner in the receiver with whole path fingers system show the BER performance degradation due to the poor channel estimation [13], [14]. Multiple pre-Rake filtering is one of possible way

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to reduce the Rake combining problem with weak peaks in the receiver. In this case, the received signals show the several strong peaks as number of pre-Rake filters is not optimal. So the Rake combiner can maximize these peaks with the conjugate terms of these strong peaks. These peaks are enough strong to be robust to the noise effect, so Rake combiner can accurately estimate the channel characteristic to maximize the SNR. From this reason, multiple pre-Rake filters and Rake combiner system can obtain the gain from the different channel impulse responses between uplink and downlink in the TDD system. In this paper, we propose the Rake combiner based on multiple pre-Rake filters in the transmitter to increase the resolvable multipath term and maximize the SNR of received signal on the down link. The received signal can be combined several times with 1 or several chip durations apart and the SNR is maximized in our proposed system using Rake receiver. This paper is organized as follows. The proposed system is described in Sect. 2. In Sect. 3, we analyze the performance of the proposed system. In Sect. 4, we show the simulation results. Finally, conclusion is given in Sect. 5.

2. Proposed System

2.1 Conventional Pre-Rake System

In Time Division Duplexing (TDD), the same carrier is used for both uplink and downlink in different time slots. One property of such a system is that, since the same frequency is used, the channel characteristics are nearly the same in both links, provided the channel does not change rapidly. This fact also implies that knowledge of the channel impulse response, which is estimated upon reception, can be used to achieve multipath diversity gain using signal processing at the transmitter, instead of employing a Rake receiver at the mobile station. This technique, known as pre-Rake, is first suggested by Esmailzadeh [3]. The block diagram of the conventional pre-Rake system is shown in Fig. 1. With a pre-Rake transmitter at the BS, the mobile station needs just a conventional receiver instead of a more complex Rake receiver, and can be kept simple and cheap, since the signal processing is transferred to the base station. Even though the pre-Rake has a variety merits for increasing the system performance, this system is sensitive to the Doppler frequency. In TDD based system, the channel impulse response between uplink and downlink are slightly different, so the pre-Rake filtering signals are not optimal in the receiver side. In this case, the Rake combiner in the receiver is reasonable approach to increase the system performance. In this paper, we propose multiple pre-Rake filtering based on the predicted channel impulse response in the transmitter and Rake combiner in the receiver for improving system performance.

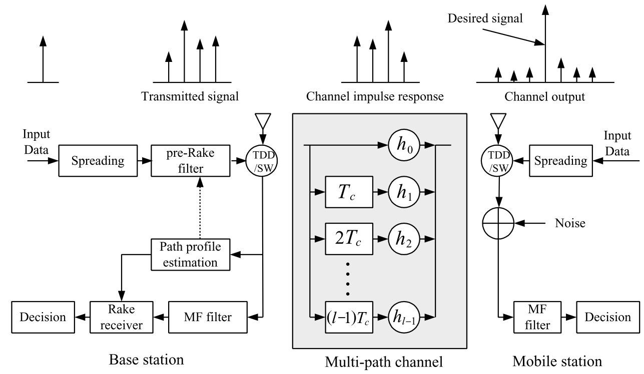

Fig. 1 The conventional pre-Rake system.

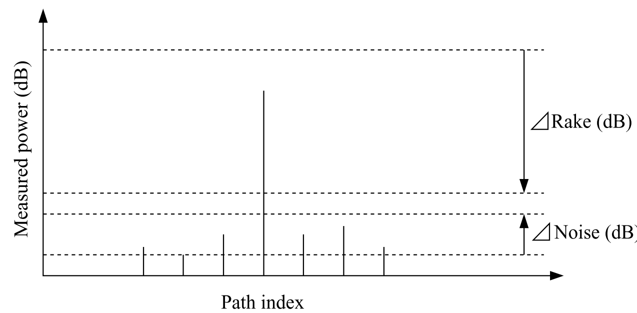

Fig. 2 The received signal path pattern using the pre-Rake filtering in the transmitter.

2.2 Proposed System

Figure 2 shows the received signal path pattern using the pre-Rake filtering in the transmitter. The conventional pre-Rake system uses the uplink channel impulse response for pre-Rake filtering operation in the downlink, so the received signal path pattern shows one strong peak and many weak peaks. In general, Rake combiner can maximize the SNR of weak signals, but pre-Rake system uses the several paths to make a strong peak. Therefore, the weak signals are strongly effected by the backgroud noise. It means that the weak signals tend to degrade slightly the average BER performance, since the accuracy of channel estimation tends to deteriorate on the low power peaks. Multiple pre-Rake filtering is one of possible way to reduce the Rake combining problem with weak peaks in the receiver. In this case, the received signals show the several strong peaks as number of pre-Rake filters is not optimal. So the Rake combiner can maximize these peaks with the conjugate terms of these strong peaks. These peaks are enough strong to be robust to the noise effect, so Rake combiner can accurately estimate the channel characteristic to maximize the SNR. Moreover, we consider the predicted channel impulse response and pre-processing of eigenvalue approach to obtain several strong peaks to reduce the color noise term. The received multiple pre-Rake filtered signals include the colored noise, since the received peaks term are highly correlated in temporal. In this case, the Rake receiver can obtain the optimal signals using the same number of the Rake fingers like pre-Rake filters in the transmitter without considering the weak peak signals, since the eigen-filter is an optimal filter. Moreover, the reason why we consider the multiple pre-Rake filters in the transmitter and Rake combiner in the receiver is to reduce demerit of the pre-Rake. Since the signals of the desired user and interfering users are subject to identical multipath fading channel, the level of the desired signal is identical to that of the signals of interfering users. Therefore, when the maximal ratio combining is utilized for the detection method, the interference is also emphasized, and hence, the system performance also degrades. On the other hand, in the pre-Rake system, the desired signal is only emphasized and other users' signals are randomized by the pre-Rake system. Therefore, the pre-Rake has the ability to suppress other user interference. From this reason, the pre-rake system shows better BER performance than that of the Rake system [7]. However, the pre-Rake system is sensitive to Doppler frequency, so the BER performance is degraded with increasing the Doppler frequency. When we consider the Rake combiner in the transmitter, we can compensate the Doppler effect while maintaining the merit of pre-Rake for multiuser case in high Doppler frequency. The block diagram of the proposed system is shown in Fig. 3. The proposed system consists of P pre-Rake filters at the base station and a Rake receiver at the mobile station. The path profile estimation part provides the parameters to the Rake and the pre-Rake filters. In the reverse link, the transmitted signal from the mobile station reaches the base station through the multipath channel. The signals whose propagation delay difference is more than the chip duration T_c are separated and combined by the Rake receiver by using estimated channel impulse response information that is calculated by the path profile estimation block. This path profile estimation block selects the multipath signal with high power for maximum ratio combining (MRC). In the conventional pre-Rake system, the input signal is modified to the time reverse channel impulse response by one pre-Rake filter with the estimated path profile in the downlink. In our proposed system, we consider the multiple pre-Rake filters to increase the resolvable multipath term and reduce the performance degradation due to the poor channel estimation accuracy of low peak signals. If we could find and set the optimum pre-Rake tap coefficients, multiple pre-Rake filters achieve better BER performance than that of conventional pre-Rake system, since these tap coefficients are optimum. Here, we use the following algorithm to set the optimum coefficients of multiple pre-Rake filters. First, each received peak signal by the matched filter is measured in the uplink channel state and the predictor to fit the fading envelope to each of the measured peaks.

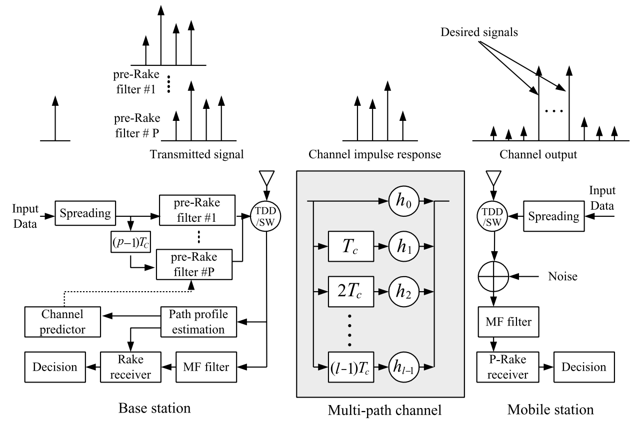

Fig. 3 The proposed system using multiple pre-Rake filters in transmitter and a Rake combiner in receiver.

The predictor requires heavy computation complexity to improve the accuracy of the predicted channel impulse response. In this paper, we use LMS method to fit a second order polynomial to each of the measured peaks with low complexity. Next, we calculate the next fading of the sub-slots of the next link using this polynomial values [15]. Finally, we calculate the channel coefficients of multiple pre-Rake filters using eigenvalue approach [16], [17]. The input signal is modified to the time reverse channel response by the multiple pre-Rake filters with the calculated channel coefficients to reduce the mismatch of estimated channel impulse response and next link fading. Furthermore, we consider the Rake combiner in the receiver to maximize the SNR of received signal using the conjugate term of slightly different channel impulse response between predicted and real downlink channel. The Rake receiver separates these time-different received signals with strong peaks and then combines these separated signals, so we can achieve better BER performance than that of the conventional pre-Rake system.

3. Performance Analysis

The multipath channel model in [3] is used in this paper. The complex path impulse response of the channel is given by

$$h(t) = \sum_{l=0}^{L-1} h_l \delta(t - lT_c) \tag{1}$$

where L is the number of channel paths, h_l represents the complex path strength, and $\delta(t - lT_c)$ is the propagation delay for path l. Without loss of generality, we can take the normalization $E[h_l^2] = 1$. We analyze the multiple pre-Rake filtering based on the predicted channel impulse response in the transmitter and a Rake combiner in the receiver, and assume that the channel impulse response period time is same for the up and down links but the path gains are time variant.

3.1 Multiple Pre-Rake Filters in the Transmitter

The transmitted signal for user k with P pre-Rake filters can be represented by

$$S_k(t) = \sqrt{\frac{E_c}{2P\sum_{l=0}^{L-1}|h_{k,l}|^2}}\sum_{p=0}^{P-1}\sum_{m=0}^{L-1}\hat{h}^*_{k,m} \cdot d_k(t+mT_c+pT_c) \cdot c_k(t+mT_c+pT_c) \quad (2)$$

where $P\sum_{l=0}^{L-1}|h_{k,l}|^2$ is the normalization factor of transmitted signal for proposed system, and P is the number of pre-Rake filters. $\hat{h}^*_{k,m}$ is the channel impulse response conjugate term for user k, E_c is the transmitted chip energy, $d_k(t)$ is the modulated data stream with symbol duration T, $c_k(t)$ is the spreading code with ± 1 chips of duration T_c and spreading factor $N_{SF} = T/T_c$. The symbols and chips waveforms are rectangular.

3.2 Rake Combiner in the Receiver

The received signal at receiver side is given by

$$r_k(t) = \sqrt{\frac{E_c}{2P\sum_{l=0}^{L-1}|h_{k,l}|^2}}\sum_{p=0}^{P-1}\sum_{l=0}^{L-1}\sum_{m=0}^{L-1} \cdot d_k(t-lT_c+mT_c+pT_c) \cdot c_k(t-lT_c+mT_c+pT_c)\hat{h}^*_{k,m}h_{k,l} + n(t) \quad (3)$$

where $n(t)$ is the zero mean AWGN. From (2) and (3), we can see that P channel outputs include $2L-1$ paths with a strong peak due to $S_k(t)$ at a delay equivalent to $m+l=L$. The output of user k matched filter (MF) in the receiver is given by

$$r_k(t) = \sqrt{\frac{E_c}{2P\sum_{l=0}^{L-1}|h_{k,l}|^2}}\sum_{q=-P-L+2}^{L-1} d_k(t-qT_c) \cdot c_k(t-qT_c)\eta_{k,q} + n(t) \quad (4)$$

where $\eta_{k,q} = \hat{h}^*_{k,m} \otimes h_{k,l}$, and $\otimes$ denotes convolution. This signal $r_k(t)$ is correlated with the spreading code and integrated over T symbol duration to obtain the decision variable before the despreading block

$$Z = \int_{LT_c}^{LT_c+T}(Re[r_k(t)\odot c_k(t)] + Im[r_k(t)\odot c_k(t)])dt \quad (5)$$

where the operation $\odot$ means that the real and imaginary components of the received signal and of the spreading code are correlated rerspectively. Our proposed system is further processed with a Rake receiver. In the TDD system, the received pre-Rake filtering signal is not optimum in term of the SNR. This is because the pre-Rake filtering signal using the predicted channel impulse response and real next link channel state are slightly different. So Rake receiver can maximize the SNR of the received signal, even though we use the pre-Rake filtering in the transmitter. Considering that the spreaded data symbol $d_k(t)c_k(t)$ is constant and equals to d over the T symbol duration. In Eq. (4), C_k is the discrete aperiodic cross correlation function defined [18]. Denoting $C_k(t-qT_c)$ by C_k and utilizing $C_k(t-qT_c) = C_k(-(t-qT_c))$, we have the decision variable

$$Z_{pro} = N_{SF}\sqrt{\frac{2E_c}{P\sum_{l=0}^{L-1}|h_{k,l}|^2}}\sum_{q=-L+1}^{P+L-2}|\eta_{k,q}|^2\cdot d + I_{SELF} + I_{MAI} + n = D + I_{SELF} + I_{MAI} + n \quad (6)$$

where D is desired signal, I_{SELF} is the self interference, I_{MAI} is the multiple access interference and n is the white gaussian noise. The variance of the self interference, the multiple access interference and the white gaussian noise are given by

$$var(I_{SELF}) = \frac{N_{SF}E_c}{P\sum_{l=0}^{L-1}|h_{k,l}|^2}\sum_{q=-2(L-1),\neq 0}^{2(P+L-2)}|\eta_{0,q} * \eta^*_{0,q}|^2 \quad (7)$$

$$var(I_{MAI}) = N_{SF}E_c\sum_{k=1}^{K-1}\sum_{q=-2(L-1)}^{2(P+L-2)}\left[|\eta_{k,q} * \eta^*_{0,q}|^2\xi_k + |\eta_{k,q} * \eta^*_{0,q}|^2\right] \quad (8)$$

$$var(n) = N_0N_{SF}\sum_{q=-L+1}^{P+L-2}|\eta_q|^2 \quad (9)$$

where ξ_k is the orthogonal factor, $\eta_q = \sum_{k=1}^{K}\eta_{k,q}$ where K is the number of users. The SINR of our proposed system can be obtained from (6), (7), (8) and (9) as

$$SINR_{pro} = \frac{D^2}{var(I_{SELF}) + var(I_{MAI}) + var(n)}. \quad (10)$$

Now, we consider the performance comparison with conventional pre-Rake system and our proposed system with optimum coefficients of multiple pre-Rake filters calculated from the predicted channel impulse response.

3.2.1 Case with Optimum Coefficients of Multiple Pre-Rake Filters Calculated from the Predicted Channel Impulse Response

Here, we will discuss the optimum condition to set the channel coefficients of multiple pre-Rake filters using the predicted channel impulse response to achieve good SNR for the Rake receiver. First, we consider single user case. In this case, I_{SELF} is usually negligible for large spreading factor, and thus, we will ignore it at this stage for simplicity. The SNR of our proposed system for single user case can be obtained from (6) and (9) as

$$SNR_{pro} = \frac{2N_{SF}E_c \sum_{q=-L+1}^{P+L-2} |\eta_q|^2 \cdot d}{N_0}. \tag{11}$$

The SNR of the conventional pre-Rake system can be represented by

$$SNR_{pre-Rake} = \frac{2N_{SF}E_c \sum_{q=-L+1}^{L-1} \eta_q \cdot d}{N_0}. \tag{12}$$

Here, we let

$$X_q = \hat{h}_q^*, \quad q = 0, 1, 2, .., P + L - 2. \tag{13}$$

Equation (13) is the assosciate of the pre-Rake filtering tap coefficient terms. The signals considered as time reversed channel impulse response are transmitted in the pre-Rake system, and we consider P pre-Rake filtering, so the index terms are defined from 0 to $P+L-2$. We will get $\eta_q = X_q \otimes h_l$, and $\sum_{q=0}^{P+L-2} |X_q|^2 = 1$. Now, we will consider how to choose X_q in order to maximize the SNR of the proposed system using the predicted channel impulse response h_l. It means that the Rake receiver can maximize the SNR of the received signal. Now, we let

$$\eta = [\eta_{-L+1}, \eta_{-L+2}, \cdots, \eta_{P+L-2}]^T \tag{14}$$

$$X = [X_0, X_1, \cdots, X_{P+L-2}]^T \tag{15}$$

$$\mathbf{H} = \begin{bmatrix} h_0 & 0 & 0 & \ldots & 0 \\ h_1 & h_0 & 0 & \ldots & 0 \\ h_2 & h_1 & h_0 & \ldots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \ldots & h_{L-1} & h_{L-2} \\ 0 & 0 & \ldots & 0 & h_{L-1} \end{bmatrix}. \tag{16}$$

We get $\eta = \mathbf{H}X$ and the SNR of the proposed system can be presented by

$$\begin{aligned} SNR_{pro} &= \frac{2N_{SF}E_c X^H \mathbf{H}^H \mathbf{H} X}{N_0} \\ &= \frac{2N_{SF}E_c X^H M X}{N_0} \end{aligned} \tag{17}$$

where superscript H denotes conjugate transpose and M is the correlation matrix $M = \mathbf{H}^H\mathbf{H}$. From [16], we can see that M is toeplitz, and all elements on its main diagonal are equal to $\sum_{l=0}^{L-1} |h_l|^2$. The choice for the proposed system that leads to maximum output SNR is unique up to a scale factor and can be found as the solution to the following problem.

$$(SNR_{pro})_{max} = arg\ max\ X^H M X \tag{18}$$

The maximum SNR becomes

$$SNR_{pro} = \frac{2N_{SF}E_c \lambda_{max}}{N_0} \tag{19}$$

where λ_{max} is the largest eigen values of the correlation matrix $X^H M X$, If we could find the maximum eigen value λ_{max}, we can find that

$$\lambda_{max} \geq \sum_{l=0}^{L-1} |h_l|^2 \tag{20}$$

since the maximum eigen-filter is the optimum filter. From (20), we also find that

$$\sum_{q=-L+1}^{P+L-2} |\eta_q|^2 \geq \sum_{q=-L+1}^{L-1} \eta_q = \sum_{q=-L+1}^{L-1} |h_q|^2. \tag{21}$$

$$\begin{aligned} SNR_{pro} &= \frac{2N_{SF}E_c \sum_{q=-L+1}^{P+L-2} |\eta_q|^2 \cdot d}{N_0} \\ &\geq \frac{2N_{SF}E_c \sum_{q=-L+1}^{L-1} \eta_q \cdot d}{N_0} \\ &\geq SNR_{pre-Rake}. \end{aligned} \tag{22}$$

The right-hand expression of Eq. (21) shows the received signal from one pre-Rake filtering signal. Therefore, the peak includes one pre-Rake filtering signal with L paths, and channel impulse response with L paths. Since our proposed system uses the coefficients that is associated with the largest eigen value λ_{max}, our proposed system can achieve better BER performance than that of the conventional pre-Rake system or Rake system.

3.2.2 Case with Non Optimum Coefficients of Multiple Pre-Rake Filters

Here, we consider the case with non optimum coefficents. It means that we do not use the predicted channel impulse response, only use the estimated channel impulse response. In this case, the coefficients of the multiple pre-Rake filters are not optimum, since the channel impulse responses of up and down links are different in the TDD system. So the conventional pre-Rake system shows bad system performance. But our proposed system can achieve better system performance than that of the conventional pre-Rake system, since

$$\begin{aligned} \sum_{q=-L+1}^{P+L-2} |\eta_q|^2 &= \sum_{q=-L+1}^{L-1} |\eta_q|^2 + \sum_{q=-L+1, P\neq 0}^{P+L-2} |\eta_q|^2 \\ &\geq \sum_{q=-L+1}^{L-1} |\eta_q|^2. \end{aligned} \tag{23}$$

So our proposed system can achieve better BER performance than that of one pre-Rake filter in the transmitter and Rake combiner in the receiver. Furthermore, the conventional pre-Rake transmitter only multiplies the signal with time-inverted complex conjugate of the reverse link channel impulse response to make a point strong peak for achieving MRC effect, but the channel impulse response of up and down links are different in the TDD system. When we use Rake combiner in the receiver, we can maximize the SNR of the received signal using the conjugate term of different channel impulse response between up and down links. So one pre-Rake filter in the transmitter and Rake combiner in the receiver system can achieve better BER performance than that of the conventional pre-Rake system.

$$\sum_{q=-L+1}^{L-1} |\eta_q|^2 \geq \sum_{q=-L+1}^{L-1} \eta_q = \sum_{q=-L+1}^{L-1} |h_q|^2. \qquad (24)$$

The right-hand expression of Eq. (24) shows the received signal from one pre-Rake filtering signal. Therefore, the peak includes one pre-Rake filtering signal with L paths, and channel impulse response with L paths. From (23) and (24), our proposed system can achieve better BER performance than that of the conventional pre-Rake system. In multiuser case, we will show the BER performance of our proposed system using computer simulation.

4. Computer Simulated Results

Table 1 shows the simulation parameters. Each TDD time slot consists of 10 sub slots ($M = 10$) and has a length of 25 ms (thus, $T_{sub-slot} = 2.5$ ms). $N_p = 4$ and $N_d = 36$ are assumed. Data modulation and spreading modulation are QPSK and BPSK, respectively. The spreading sequences are gold and walsh sequences with transmission rate of 16 ksps and their spreading factors are N_{SF}=63 and 64 chips per symbol, respectively (i.e., $1/T = 16$ ksps). The power delay profile shape assumed in this simulation is a decayed model. Each path is subject to be independent Rayleigh fading as shown in Fig. 4. In this model, $L = 4$ path Rayleigh fadings have exponential shapes with path separation of $T_{path} = 976$ nsec. This causes a severe frequency selective fadings channel. The maximum Doppler frequency is assumed to be from 20 Hz to 200 Hz. Figures 5 and 6 show the BER performance of the conventional pre-Rake system, the conventional pre-Rake system in the transmitter and Rake combiner with whole path fingers in the receiver, and our proposed systems. The conventional pre-Rake system uses once the selected multipath terms to achieve MRC effect like Rake receiver. However, our proposed system uses efficiently the multipath terms by multiple pre-Rake filters to reduce the noise effects, and thus, the SNR of our proposed system is maximized by using Rake combiner in receiver. Particularly, eigenvalue approach based on the predicted channel impulse response for multiple pre-Rake filters achieves better BER performance than that of the conventional pre-Rake system. So our proposed system with predicted 3 pre-Rake filters achieves the improvement of 1 dB at the BER of 10^{-3} and Doppler frequency of 20 Hz. With increasing the Doppler frequency, our proposed system achieves better BER performance than that of the conventional pre-Rake system at Doppler frequency of 200 Hz, since the channel state information is rapidly changed for both uplink and downlink. So the conventional pre-Rake system shows poor BER performance, whereas our proposed systems successfully compensate the channel difference. The conventional pre-Rake system in the transmitter and Rake combiner with whole path fingers in the receiver show worse BER performance than that of the conventional pre-Rake system for Doppler frequency of 20 Hz. This is because the weak paths tend to degrade slightly the average BER performance, since the accuracy of channel estimation tends to deteriorate on the low power peaks. With increasing the E_b/N_0, the conventional pre-Rake system in the transmitter and Rake combiner with whole path fingers in the receiver show better BER performance than that of the conventional pre-Rake system. This is because the noise effect is degraded with increasing the E_b/N_0, so the Rake combiner can estimate the channel characteristic for low power peaks. From this reason, the conventional pre-Rake system in the transmitter and Rake combiner with whole path fingers in the receiver show better BER performance than the conventional pre-Rake system in high E_b/N_0. Figures 7 and 8 show the BER performance of the conventional pre-Rake sys-

Table 1 Simulation parameters.

Transmission rate	16 [Ksymbol/s] TDD
Spreading code	Gold/Walsh sequences
Spreading Factor	63/64
Modulation (Data)	QPSK
Modulation (Spreading)	BPSK
Frame size	40 symbols ($N_p = 4$, $N_d = 36$)
Channel model	4-Rayleigh wave model (1 chip delay)
Doppler frequency	20–200 Hz

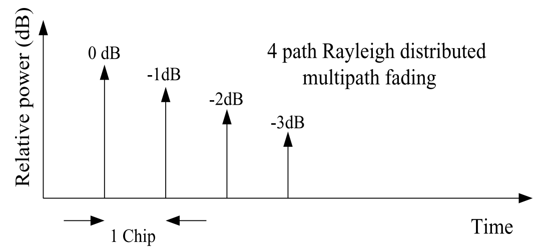

Fig. 4 The channel model.

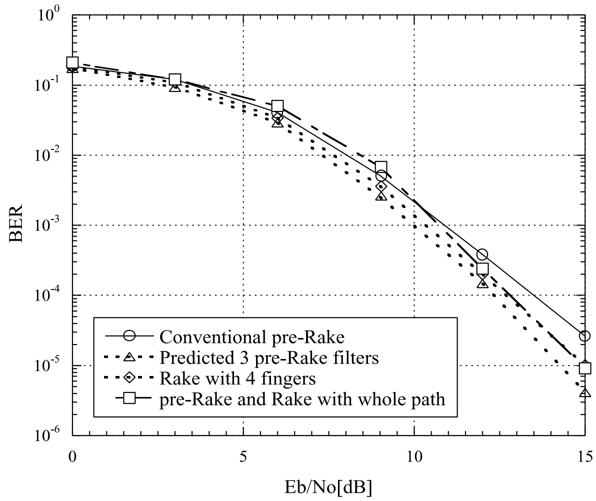

Fig. 5 BER performance of the conventional pre-Rake system, Rake receievr with 4 fingers, conventional pre-Rake and Rake combiner with whole path fingers, and proposed systems based on predicted channel impulse response in single user case using gold sequence with 4 paths and Doppler frequency of 20 Hz.

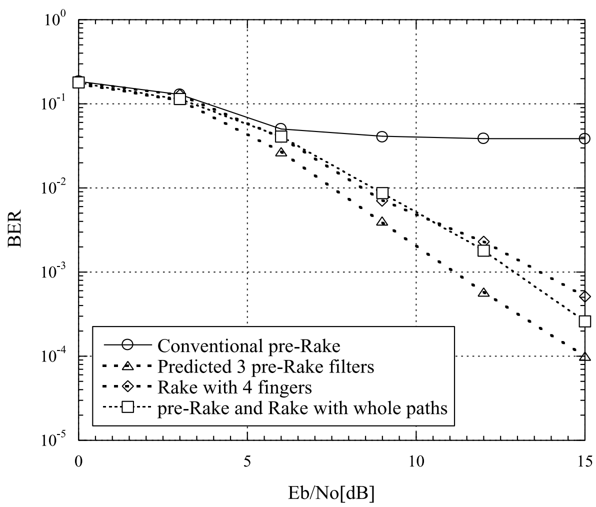

Fig. 6 BER performance of the conventional pre-Rake system, Rake receievr with 4 fingers, conventional pre-Rake and Rake combiner with whole path fingers, and proposed systems based on predicted channel impulse response in single user case using gold sequence with 4 paths and Doppler frequency 200 Hz.

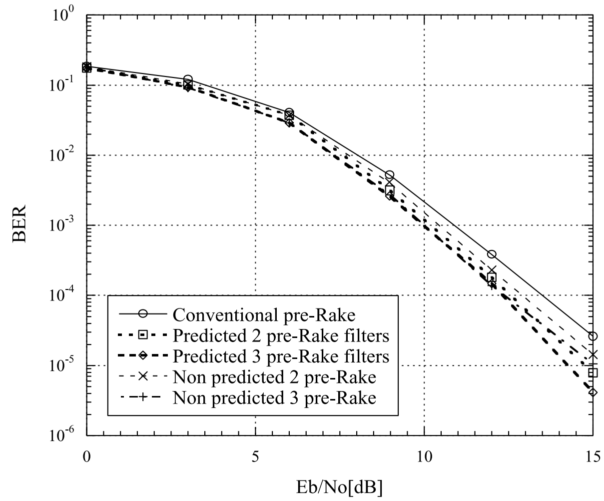

Fig. 7 BER performance of the conventional pre-Rake system and the proposed systems based on predicted and non predicted channel impulse response in single user case using gold sequence with 4 paths and Doppler frequency of 20 Hz.

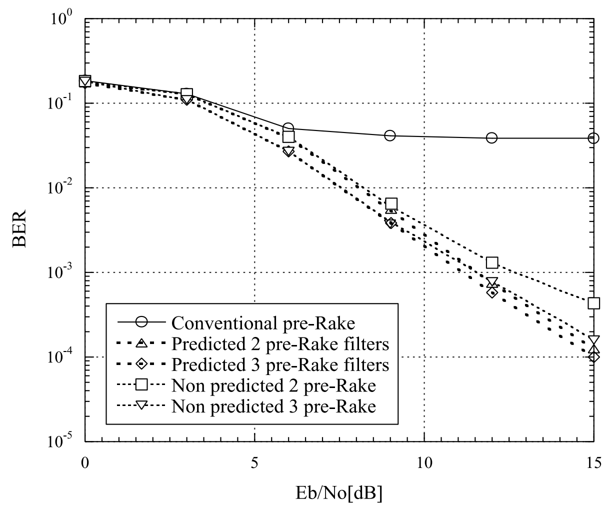

Fig. 8 BER performance of the conventional pre-Rake system and the proposed systems based on predicted and non predicted channel impulse response in single user case using gold sequence with 4 paths and Doppler frequency of 200 Hz.

tem and the proposed systems based on predicted and non predicted channel impulse response in single user case using gold sequence with 4 paths and Doppler frequency 20 and 200 Hz. The proposed systems achieve better BER performance than that of the conventional pre-Rake system since our proposed systems are efficiently processing using eigenvalue approach based on the predicted channel impulse responses to maximize the received signal in the Rake combiner in the receiver. From this reason, our proposed system achieve better BER performance that of the conventional pre-Rake in low Doppler frequency. With increasing the Doppler frequency, the channel state of uplink and downlink is rapidly changed, so the conventional pre-Rake system shows the error floor. Figure 9 shows the BER performance comparison between non-orthogonal coded and orthogonal coded multiple pre-Rake filters in the transmitter based on the predicted channel impulse response and Doppler frequency of 20 Hz, for single, 10, and 20 user cases. The orthogonal coded system achieves better BER performance than that of the non-orthogonal coded system in low E_b/N_0 in single user. With increasing E_b/N_0, the non-orthogonal coded system does not show gradient degradation in the BER performance curve, but the orthogonal coded system shows gradient degradation in the BER performance curve in high

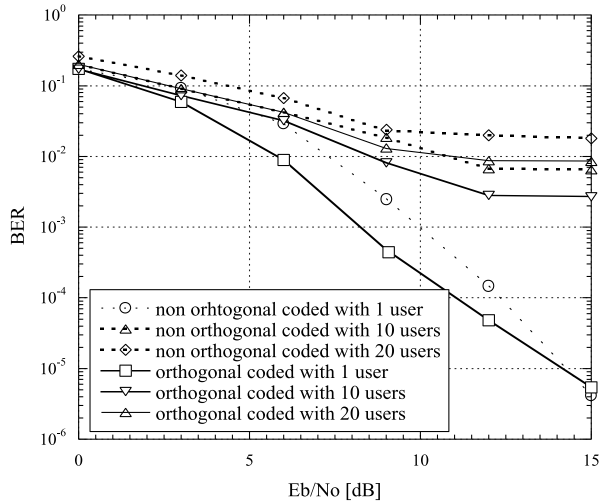

Fig. 9 BER performance of orthogonal and non-orthogonal coded system for various user cases with predicted 3 pre-Rake filtering system and Doppler frequency of 20 Hz.

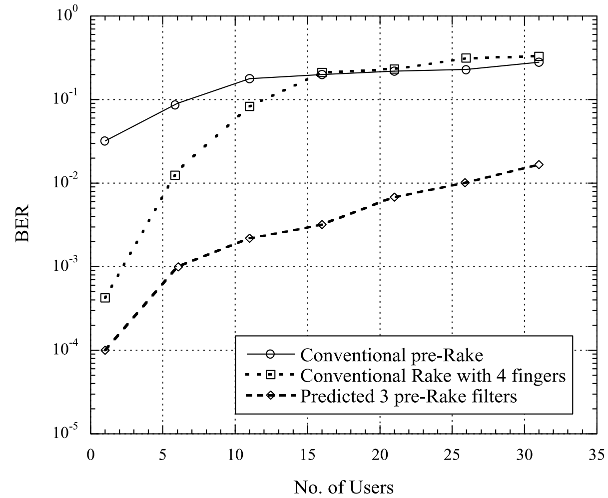

Fig. 11 BER performance of the conventional pre-Rake system and our proposed systems using Walsh sequence versus the number of users for $E_b/N_0 = 15$ dB, number of paths is 4, and Doppler frequency of 200 Hz.

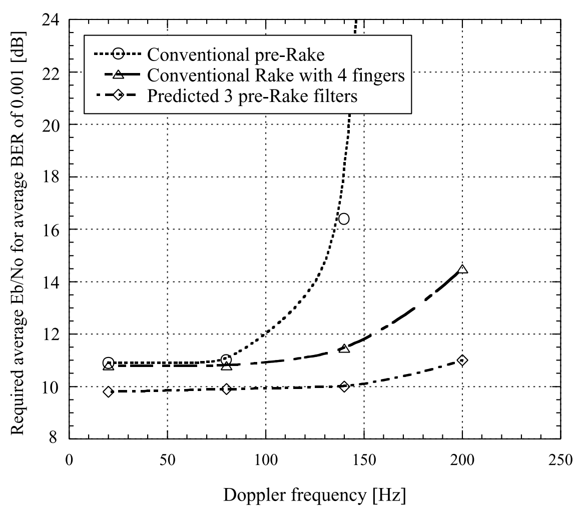

Fig. 10 Required average E_b/N_0 for satisfying average BER of 10^{-3} of conventional pre-Rake system and our proposed system for various Doppler frequency and single user case.

E_b/N_0. This is due to different auto correlation characteristics between non-orthogonal coded and orthogonal coded systems. The orthogonal coded system has very poor auto-correlation characteristics, so this introduces gradient degradation in the BER performance curve in high E_b/N_0. With increasing the number of users, the orthogonal coded systems show better BER performance than those of the non-orthogonal coded system. As mentioned above, it is better to use the orthogonal code for our system in multiuser cases. Now we show the difference between the system performance of the conventional Rake system and pre-Rake system. Since the signals of the desired user and interfering users are subject to identical multipath fading channel, the level of the desired signal is identical to that of the signals of interfering users. Therefore, when the maximal ratio combining is utilized for the detection method, the interference is also emphasized, and hence, the system performance degrades. On the other hand, in the pre-Rake system, the only desired signal is emphasized and other users' signals are randomized by the pre-Rake system. Therefore, the pre-Rake has the ability to suppress other user interference. From this reason, the pre-rake system shows better BER performance than that of the Rake system. However, the pre-Rake system is sensitive to Doppler frequency, so the BER performance is degraded with increasing the Doppler frequency. Figure 10 shows the required average E_b/N_0 for satisfying average BER of 10^{-3} in the conventional pre-Rake system, Rake system with 4 fingers, and our proposed system for various Doppler frequencies and single user case. Our proposed system requires the smallest E_b/N_0 for satisfying the BER of 10^{-3} in various Doppler frequencies. This is because the pre-Rake system is sensitive to Doppler frequency, so the poor BER performance is shown in high Doppler frequency. The Rake system shows better BER performance than that of pre-Rake system in high Doppler frequency, however, the received signal is not emphased like pre-Rake filtered signals, so the Rake system is more effected by the noise. Moreover, our proposed system considers the predicted channel impulse response and eigenvalue approach to maximize the received signals. From these reasons, our proposed system shows better system performance than those of the conventional pre-Rake and the Rake system with 4 fingers. Figure 11 shows the BER performance of the conventional pre-Rake system, Rake system with 4 fingers, and our proposed systems using Walsh sequence versus various number of users for $E_b/N_0 = 15$ dB, number of paths is 4, and Doppler frequency of 200 Hz. In the pre-Rake system, the only desired signal emphasized and other users' signals are randomized by the pre-Rake system. However, this system is so sensitive to Doppler frequency, so the pre-Rake system shows approximately the same BER performance as Rake system. But our proposed system can compensate the Doppler frequency effect of the pre-Rake system with keeping above mentioned merit. So our proposed system shows better BER performance than those of the pre-Rake and Rake systems with increasing the active users. Even though the pre-Rake system has the ability to suppress other user interference, it is not efficient to maximize the received signal in high Doppler frequency. So the pre-Rake system shows worse BER performance than that of our proposed system with increasing the number of users. From Eq. (8), in our proposed system, Rake combiner is utilized for the detection method. So the maximized signal can keep the orthogonality better than the pre-Rake system. Moreover, our proposed system compensate the Doppler frequency effect. From this reason, our system achieves better BER performance than that of the pre-Rake system with increasing the number of users in Doppler frequency of 200 Hz.

5. Conclusions

We have proposed multiple pre-Rake filters based Rake combining system. The proposed system involves multiple pre-Rake filters in the transmitter and a Rake receiver in the receiver. Our proposed system uses multiple pre-Rake filters based on the eigenvalue approach using the predicted channel impulse response in the transmitter, so the receiver can maximize the received signals by using Rake combiner. Moreover, our proposed system can maintain the merit of the pre-Rake system to suppress other user interference in downlink for high Doppler frequency. It is shown that our proposed system achieves better BER performance than the conventional pre-Rake system against the multiuser interference in high Doppler frequency.

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References

[1] K.S. Gilhousen, I.M. Jacobs, R. Padovani, and A.J. Viterbi, "On the capacity of a cellular CDMA system," IEEE Trans. Veh. Technol., vol.40, no.2, pp.303–312, May 1991.
[2] R. Kohno, R. Meidan, and L.B. Milstein, "Spread spectrum access methods for wireless communications," IEEE Commun. Mag., vol.33, pp.58–67, Jan. 1995.
[3] R. Esmailzadeh and M. Nakagawa, "Pre-Rake diversity communication for direct sequence spread spectrum mobile communication system," IEICE Trans. Commun., vol.E76-B, no.8, pp.303–312, Aug. 1993.
[4] R. Esmailzadeh, E. Sourour, and M. Nakagawa, "Pre-RAKE diversity combining in time division duplex CDMA mobile communications," Proc. PIMRC'95, vol.2, pp.431–435, 1995
[5] I. Jeong and M. Nakagawa, "A time division duplex CDMA system using asymmetric modulation scheme in duplexc hannel," IEICE Trans. Commun., vol.E82-B, no.12, pp.1956–1963, Dec. 1999.
[6] Z. Pu, X. You, S. Cheng, and H. Wang, "Transmission and reception of TDD multicarrier CDMA signals in mobile communications system," Proc. VTC'99, vol.3, pp.2134–2138, 1999.
[7] A.N. Barreto and G. Fettweis, "On the downlink capacity of TDD-CDMA systems using a pre-RAKE," Proc. Globecom'99, vol.1a, pp.117–121, 1999.
[8] I. Jeong and M. Nakagawa, "A novel transmission diversity system in TDD-CDMA," IEICE Trans. Commun., vol.E81-B, no.7, pp.1409–1416, July 1998.
[9] R.L.-U Choi, K.B. Letaief, and R.D. Murch, "Transmit diversity combining for wideband DS/CDMA in wireless communication systems," Proc. ISCC 2000, pp.717–722, 2000.
[10] S. Zazo, F. Bader, and J.M. Paez-Borrallo, "Pre-RAKE and multiuser detection techniques in UTRA-TDD systems," Proc. VTC 2000, vol.3, pp.2069–2072, 2000.
[11] J.-B. Wang, M. Zhao, S.-D. Zhou, and Y. Yao, "Optimal sequences to suppress the multiuser interference in the downlink of the TDD-CDMA systems," IEICE Trans. Commun., vol.E83-B, no.8, pp.1656–1663, Aug. 2000.
[12] G.E. Bottomley and T. Ottosson, "A generalized Rake receiver for interference suppression," IEEE J. Sel. Areas Commun., vol.18, no.8, pp.1536–1545, Aug. 2000.
[13] S. Fukumoto, M. Sawahashi, and F. Adachi, "Matched filter based Rake combiner for wideband DS-CDMA mobile radio," IEICE Trans. Commun., vol.E81-B, no.7, pp.1384–1391, July 1998.
[14] S. Fukumoto, K. Okawa, K. Higuchi, M. Sawahashi, and F. Adachi, "Path search performance and its parameter optimization of pilot symbol assisted coherent Rake receiver for W-CDMA mobile radio," IEICE Trans. Fundamentals, vol.E83-A, no.11, pp.2110–2119, Nov. 2000.
[15] C. Ahn and I. Sasase, "The effects of modulation combinations, target BER, Doppler frequency, and adaptation interval on the performance of adaptive OFDM in the broadband mobile channel," IEEE Trans. Consumer Electronics, vol.48, no.1, pp.167–174, Feb. 2002.
[16] S. Haykin, Adaptive filter theory, Prentice-Hall, 3rd ed., 1996.
[17] D. Park, M. Yamada, Y. Hara, and Y. Kamio, "Adaptive antenna array based on the eigenvalue approach for CDMA systems," Proc. MDMC'01, pp.373–380, June 2001.
[18] M. Purseley, "Performance evaluation for phase coded spread spectrum multiple access communication-part I: System analysis," IEEE Trans. Commun., vol.25, no.8, 1997.

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