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Computational Complexity and Performance of RAKE Receivers with Channel Estimation for DS-UWB

Hiroyuki SATO^{†a)}, Student Member and Tomoaki OHTSUKI^{††b)}, Member

SUMMARY In this paper, we evaluate the computational complexity and the performance of the RAKE receivers for the Direct Sequence—Ultra Wideband (DS-UWB) with considering the accuracy of channel estimation in a multipath channel. As RAKE receivers for DS-UWB, we consider the maximal-ratio combining (MRC)-RAKE, the minimum mean square error (MMSE)-RAKE, and the MRC-RAKE-Equalizer that is the MRC-RAKE followed by a linear equalizer. Generally, if the channel estimation is perfect, as the number of fingers or taps increases, the performance of each receiver is improved, however the computational complexity of each receiver increases. In practice, the channel estimation is not perfect. The channel estimation error makes their performances degraded. Therefore, the performances of the RAKE receivers depend on the accuracy of channel estimation. Consequently, we evaluate the computational complexities and the Bit Error Rates (BERs) of MRC-RAKE, MMSE-RAKE, and MRC-RAKE-Equalizer with considering the accuracy of channel estimation for DS-UWB. We show that the accuracy of channel estimation affects the BER of each receiver significantly. We also show that when the accuracy of channel estimation is high, MRC-RAKE-Equalizer can achieve the better BER than MMSE-RAKE with less computational complexity, while MMSE-RAKE can achieve the better BER than MRC-RAKE-Equalizer when the accuracy of channel estimation is low.

key words: DS-UWB, MRC-RAKE, MMSE-RAKE, MRC-RAKE-Equalizer, the computational complexity, the accuracy of channel estimation

1. Introduction

Ultra Wideband (UWB) has recently attracted much attention as an indoor short range high-speed wireless communication. In IEEE 802.15 Study Group 3a, Multiband OFDM-UWB that is a carrier-based system dividing UWB bandwidth to subbands and Direct Sequence (DS)-UWB that is an impulse-based system that multiplies an input bit with the spread code and transmits by modulating the element of the symbol with a short pulse have been proposed [1], [2]. The UWB systems spread the energy from several hundred MHz to a few GHz [3]. Whereby the channel is extremely frequency selective and the received signal is composed of a significant number of multipath components that have different delays of the order of nanosecond [4]. The DS-UWB system has a fine path resolution by transmitting information with ultra short pulses. This is one of the most attractive features of the DS-UWB system and motivates the use of a

RAKE receiver. The RAKE receiver can collect effectively multipath energy and exploit the multipath diversity.

The maximal ratio combining (MRC)-RAKE receiver combines the output of the correlator of each path using the path gain and has a little computational complexity [5]–[7]. MRC-RAKE is optimum when the disturbance to the desired signal is sourced only from additive white Gaussian noise (AWGN). However, in the presence of multipath fading, intersymbol interference (ISI), and/or narrowband interference, its performance degrades.

A more suitable diversity scheme in the presence of fading and interference is the minimum mean square error (MMSE)-RAKE [7]–[9]. In MMSE-RAKE receiver, the received signals are combined using the filter parameters that minimize the mean square error (MSE) between its output and the desired signal. MMSE-RAKE can achieve the good performance even in the presence of ISI, however, the computational complexity increases significantly as the number of fingers increases.

Generally, RAKE combining needs the accurate channel estimation of each path. If the channel estimation is perfect, as the number of fingers increases, the performance of RAKE receivers is improved. However, the computational complexity of the receiver increases significantly. Thus, there is a trade-off between the performance and the computational complexity for the RAKE receivers. In practice, the channel estimation is not perfect. The channel estimation error makes their performances degraded. In addition, if the accuracy of channel estimation is low, the performance of the RAKE receivers degrades even with a large number of fingers. Therefore, it is important to evaluate the performances of the RAKE receivers with considering the accuracy of channel estimation.

The UWB multipath channel model is assumed to be constant during transmission of one packet. Moreover, channel realizations are assumed to be independent every packet. Therefore, a RAKE receiver needs to update weight coefficients every packet. In particular, in an environment with a large number of multipaths like UWB, the estimation of channel and weight coefficients needs higher computational complexity. In addition, in practical environments where UWB is used, channel may be time-varying channel where the estimation of channel and weight coefficients need to be estimated frequently. Therefore, the computational complexity of the RAKE receivers becomes one of the problems of UWB. The computational complexities of the RAKE receivers depend on the derivation methods of

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the finger weights and the number of fingers. The main issue is to give an overall idea of how the sizes of various parameters influence the computational complexity. Conventionally, the computational complexities of the systems are evaluated by the number of multiplications and/or additions [12], [13].

On the other hand, in [9] MRC-RAKE-Equalizer has been proposed where MRC-RAKE is followed by a linear MMSE equalizer to reduce the residual interference. However, the relation between the computational complexity and the performance of the receiver has not been clarified. In addition, it has not been clarified how large the effects of channel estimation are on the BER of the systems with the RAKE receiver and the equalizer.

In this paper, we evaluate the computational complexities and the BERs of MRC-RAKE, MMSE-RAKE, and MRC-RAKE-Equalizer with considering the accuracy of channel estimation for DS-UWB. First, we show that the computational complexity of MRC-RAKE is extremely lower than those of MMSE-RAKE and MRC-RAKE-Equalizer. We also show that the accuracy of channel estimation affects the BERs of MRC-RAKE, MMSE-RAKE, and MRC-RAKE-Equalizer significantly. We also show that when the accuracy of channel estimation is high, MRC-RAKE-Equalizer can achieve the better BER than MMSE-RAKE with less computational complexity, while MMSE-RAKE can achieve the better BER than MRC-RAKE-Equalizer when the accuracy of channel estimation is low. Moreover, we show that when the accuracy of channel estimation is significantly low, the BER of each receiver degrades significantly as the number of fingers increases.

This paper is organized as follows. The system model is described in Sect. 2. Section 3 presents the channel estimation. Section 4 presents the weight estimation. The computational complexity is given in Sect. 5. Sections 6 and 7 present the simulation results and comparison. Finally, we conclude this paper in Sect. 8.

2. System Model

2.1 Transmit Signal

The transmit pulse $w_{tr}(t)$ can be generated using the Ternary code of the sequence length N_c in the following form.

$$w_{tr}(t) = \sum_{i=0}^{N_c-1} s_i p_{tr}(t - iT_c) \quad (1)$$

where $p_{tr}(t)$ represents the transmitted monocycle waveform normalized to have unit energy, s_i is the i -th component of the spreading code, and T_c is the chip width. We assume that $w_{tr}(t)$ consists of N_c pulses. In this model, the pulse is assumed to include the differential effects in the transmit antenna and the receiver antenna.

The transmit signal for DS-UWB can be expressed in the following form.

$$s(t) = \sqrt{E_c} \sum_{k=-\infty}^{\infty} b_k w_{tr}(t - kT_f) \quad (2)$$

where $b_k \in \{\pm 1\}$ is the k -th transmit symbol, T_f is the frame length (the interval of one symbol), and E_c is the energy per transmitted pulse.

2.2 Channel Model

In this paper, each RAKE receiver with channel estimation is evaluated using the UWB multipath channel model based on the indoor channel measurements in the 2–8 GHz frequency band accepted by the IEEE802.15. Study Group 3a [4]. The multipath model consists of the following discrete time impulse response:

$$h(t) = \sum_{l=0}^{L_{tot}-1} h_l \delta(t - \tau_l) \quad (3)$$

where L_{tot} is the total number of paths, $\tau_l (= lT_c)$ is the delay of the l -th path component, and h_l is the l -th path gain.

2.3 Received Signal

The transmit signal is received through the UWB multipath channel. The transmit antenna and the receive antenna convert the transmit pulse $p_{tr}(t)$ to the received pulse $p_{rec}(t)$. We assume it to be the second derivative of the Gaussian pulse [3]. The received signal can be expressed as follows.

$$\begin{aligned} r(t) &= s(t) * h(t) + n(t) \\ &= \sqrt{E_c} \sum_{k=-\infty}^{\infty} b_k \sum_{l=0}^{L_{tot}-1} h_l w_{rec}(t - kT_f - \tau_l) + n(t) \end{aligned} \quad (4)$$

where $n(t)$ is additive white Gaussian noise (AWGN) with two sided power spectral density $N_0/2$, “*” represents the convolution and $w_{rec}(t)$ is the received waveform, which is expressed as follows

$$w_{rec}(t) = \sum_{i=0}^{N_c-1} s_i p_{rec}(t - iT_c). \quad (5)$$

As shown in Fig. 1, a RAKE receiver consists of L_p correlators followed by a RAKE combiner. The reference waveform $w_{ref}(t)$ in the RAKE receiver is the same as the received waveform $w_{rec}(t)$. In this paper, we employ the Selective RAKE (SRAKE) combiner [6]. In the path selection part, L_p fingers select the received signal at the delay times τ_{f_l} ($l = 0, 1, \dots, L_p - 1$) corresponding to L_p strongest paths selected based on the path gains estimated by the part of channel estimation. Each correlator correlates the received signal with the reference waveform at the delay times τ_{f_l} , and integrates over T_f .

Assuming the perfect chip synchronization between the transmitter and the receiver, the l -th correlator output $y_k^{f_l}$ for the k -th desired symbol is given by

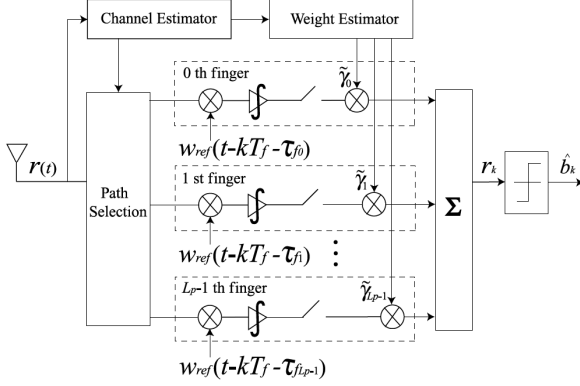


Fig. 1 The RAKE receiver.

$$y_k^{f_l} = \int_{kT_f + \tau_{f_l}}^{(k+1)T_f + \tau_{f_l}} r(t) w_{ref}(t - kT_f - \tau_{f_l}) dt$$

$$= \sqrt{E_s} b_k h_{f_l} + i_k^{f_l} + n_k^{f_l} \quad (6)$$

where $i_k^{f_l}$ is the interference component of the k -th symbol for the l -th correlator, $n_k^{f_l}$ is the noise component of the k -th symbol for the l -th correlator and E_s is the energy per symbol.

Hence, the received signal for the k -th symbol can be expressed in the following vector notation.

$$\mathbf{y}_k = \sqrt{E_s} b_k \mathbf{h} + \mathbf{i}_k + \mathbf{n}_k \quad (7)$$

where $\mathbf{y}_k = [y_k^{f_0}, y_k^{f_1}, \dots, y_k^{f_{L_p-1}}]^T$, $\mathbf{h} = [h_{f_0}, \dots, h_{f_{L_p-1}}]^T$, $\mathbf{i}_k = [i_k^{f_0}, \dots, i_k^{f_{L_p-1}}]^T$, $\mathbf{n}_k = [n_k^{f_0}, \dots, n_k^{f_{L_p-1}}]^T$, and L_p is the number of fingers of the RAKE receiver.

The output of the RAKE receiver with the number of fingers L_p for the k -th symbol can be expressed as follows.

$$r_k = \tilde{\gamma}^T \mathbf{y}_k \quad (8)$$

where $\tilde{\gamma} = [\tilde{\gamma}_0, \dots, \tilde{\gamma}_{L_p-1}]^T$ is the the finger weights of the RAKE receiver.

3. Channel Estimation

In our system, we use a data-aided approach based on using P known pilot symbols to estimate the channel impulse response. Although, it is possible to use a maximum-likelihood approach to estimate the arrival time, amplitude and phase of the channel impulse responses, the computational complexity of such an approach is too high. Consequently, we employ the general sliding correlator method for the channel estimation [9], [10]. We assume that the P known pilot symbols for the training b_k^t ($k = 0, 1, \dots, P-1$) are independent random variables. The received training signal can be expressed as follows

$$r^t(t) = \sqrt{E_c} \sum_{k=0}^{P-1} b_k^t \sum_{l=0}^{L_{tot}-1} h_l w_{rec}(t - kT_f - \tau_l) + n(t). \quad (9)$$

In Fig. 1, there are L_{est} correlators in the part of channel estimation. Hence, the output of the correlator corresponding to the L_{est} paths for the k -th pilot symbol is

$$\mathbf{y}_k^{L_{est}} = [y_k^0, y_k^1, \dots, y_k^{L_{est}-1}]^T \quad (10)$$

where L_{est} is the number of paths to be estimated. We assume that the receiver knows the optimal value of L_{est} (i.e. $L_{est} = L_{tot}$) [11]. In practice, L_{est} needs to be estimated before the channel estimation. We consider the following expectation $E\{b_k^t \mathbf{y}_k^{L_{est}}\}$.

$$\begin{aligned} E\{b_k^t \mathbf{y}_k^{L_{est}}\} &= E\{b_k^t (\sqrt{E_s} b_k^t \mathbf{h}^{L_{est}} + \mathbf{i}_k^{L_{est}} + \mathbf{n}_k^{L_{est}})\} \\ &= E\{\sqrt{E_s} |b_k^t|^2 \mathbf{h}^{L_{est}} + b_k^t \mathbf{i}_k^{L_{est}} + b_k^t \mathbf{n}_k^{L_{est}}\} \\ &= E\{\sqrt{E_s} |b_k^t|^2 \mathbf{h}^{L_{est}}\} + E\{b_k^t \mathbf{i}_k^{L_{est}}\} + E\{b_k^t \mathbf{n}_k^{L_{est}}\} \\ &= \sqrt{E_s} \mathbf{h}^{L_{est}}. \end{aligned} \quad (11)$$

We use the assumptions that $|b_k^t|^2 = 1$, $E\{\mathbf{i}_k^{L_{est}}\} = 0$, $E\{\mathbf{n}_k^{L_{est}}\} = 0$. Consequently, we can estimate the channel by cross-correlating the received training signal with the pilot symbols and averaging all the pilot symbols. The estimated path gains of the channel vector $\hat{\mathbf{h}} (= \mathbf{h}^{L_{est}})$ can be expressed as follows

$$\hat{\mathbf{h}} = \frac{1}{P \sqrt{E_s}} \sum_{k=0}^{P-1} b_k^t \mathbf{y}_k^{L_{est}} \quad (12)$$

where $\hat{\mathbf{h}} = [\hat{h}_0, \hat{h}_1, \dots, \hat{h}_{L_{est}-1}]^T$.

The MSE of the channel estimation can be expressed as follows

$$\text{MSE}_{\text{channel}} = E \left[\frac{\|\mathbf{h} - \hat{\mathbf{h}}\|^2}{\sum_{l=0}^{L_{est}-1} |h_l|^2} \right] \quad (13)$$

In our simulation, we derive the $\text{MSE}_{\text{channel}}$ by averaging the mean square error more than 1000 realization for the channel estimation. Note that the number of total paths L_{tot} is different every channel realization.

4. Weight Estimation

In Fig. 1, the finger or tap weights in RAKE receiver and Equalizer can be estimated from the received training signal in the part of weight estimator. The finger or tap weights can be derived in each receiver as follows.

4.1 MRC-RAKE

In MRC-RAKE, the l -th finger weights are determined for the l -th selected paths based on the channel estimation as follows.

$$\tilde{\gamma}_l = \hat{h}_{f_l}. \quad (14)$$

4.2 MMSE-RAKE

In MMSE-RAKE, the finger weights are determined to minimize the MSE between its output and the desired signal. It

can be expressed as follows.

$$\begin{aligned}\tilde{\gamma} &= \arg \min_{\gamma \in \mathbb{C}^{L_p}} E \left[\|b'_k - \gamma^T \mathbf{y}'_k\|^2 \right] \\ &= \arg \min_{\gamma \in \mathbb{C}^{L_p}} \left[\gamma^T E\{\mathbf{y}'_k \mathbf{y}'_k{}^T\} \gamma - \gamma^T E\{\mathbf{y}'_k b'_k{}^T\} \right. \\ &\quad \left. - E\{b'_k \mathbf{y}'_k{}^T\} \gamma + E\{b'_k b'_k{}^T\} \right]\end{aligned}\quad (15)$$

where b'_k is the k -th known pilot symbol and $\mathbf{y}'_k$ is the received signal for the k -th pilot symbol. It gives the following form by differentiating (15) with respect to γ^T .

$$E\{\mathbf{y}'_k \mathbf{y}'_k{}^T\} \gamma - E\{b'_k \mathbf{y}'_k{}^T\} = 0 \quad (16)$$

From (16) and the assumption of the independence among k -th symbol b'_k , interference $\mathbf{i}_k$, and AWGN $\mathbf{n}_k$, the two expectations in (16) can be expressed as follows

$$E\{\mathbf{y}'_k \mathbf{y}'_k{}^T\} = \mathbf{M} \quad (17)$$

$$E\{b'_k \mathbf{y}'_k{}^T\} = \mathbf{m} \quad (18)$$

where $\mathbf{M}$ is the correlation matrix of the received training signal, $\mathbf{m}$ is the cross-correlation vector between the received training signal and the pilot symbols. Therefore, the optimal finger weights of MMSE-RAKE $\tilde{\gamma}$ can be derived as follows.

$$\gamma = \mathbf{M}^{-1} \mathbf{m} \quad (19)$$

If the channel estimation is perfect and the variance of noise is a known parameter, we can derive the perfect correlation matrix. However, in practice, the channel estimation is not perfect and the variance of noise is an unknown parameter and must be estimated. Consequently, the correlation matrix must be estimated from the received training signals. The estimation of the correlation matrix from the received training signals can be derived by using the sample correlation matrix [7]. The estimated correlation matrix is given as follows

$$\hat{\mathbf{M}}_{rake} = \frac{1}{P} \sum_{k=0}^{P-1} \mathbf{y}'_k \mathbf{y}'_k{}^T. \quad (20)$$

Moreover, $\hat{\mathbf{m}}_{rake}$ can be expressed as follows.

$$\hat{\mathbf{m}}_{rake} = \frac{1}{P} \sum_{k=0}^{P-1} b_k \mathbf{y}'_k \quad (21)$$

where $\hat{\mathbf{m}}_{rake}$ is the vector that has the components of the L_p strongest path gains. In this paper, we employ this approximate solution to estimate the MMSE weights directly from the received training signal without estimating of the variance of noise. Thus, the finger weights of MMSE-RAKE can be expressed as follows.

$$\tilde{\gamma} = \hat{\mathbf{M}}_{rake}^{-1} \hat{\mathbf{m}}_{rake} \quad (22)$$

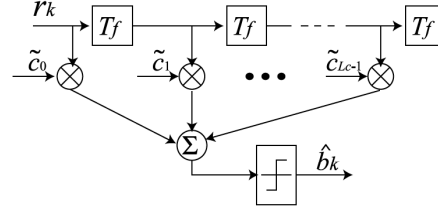


Fig. 2 The equalizer.

4.3 MRC-RAKE-Equalizer

In MRC-RAKE-Equalizer, the output of MRC-RAKE for the k -th symbol can be expressed as (8). Figure 2 shows the equalizer for MRC-RAKE-Equalizer. The equalizer has the transversal filter structure and is used to compensate for the residual ISI symbol by symbol. The tap weights are determined to minimize the MSE between its output and the desired signal as well as MMSE-RAKE.

$$\tilde{\mathbf{c}} = \arg \min_{\mathbf{c} \in \mathbb{C}^{L_c}} E \left[\|b'_k - \mathbf{c}^T \mathbf{z}'_k\|^2 \right]. \quad (23)$$

where $\mathbf{z}'_k$ is the received training signal vector as follows

$$\mathbf{z}'_k = [r_{k+(L_c-1)/2}, \dots, r_k, \dots, r_{k-(L_c-1)/2}]^T \quad (24)$$

The optimal tap weights reduce to the same form as MMSE-RAKE. Therefore, we employ the following approximate solution to the tap weights of the equalizer as well as MMSE-RAKE.

$$\tilde{\mathbf{c}} = \hat{\mathbf{M}}_{eq}^{-1} \hat{\mathbf{m}}_{eq} \quad (25)$$

where $\tilde{\mathbf{c}} = [\tilde{c}_0, \dots, \tilde{c}_{L_c-1}]^T$ and L_c is the number of taps for the equalizer, $\hat{\mathbf{M}}_{eq}$ and $\hat{\mathbf{m}}_{eq}$ can be expressed as follows, respectively

$$\hat{\mathbf{M}}_{eq} = \frac{1}{P} \sum_{k=0}^{P-1} \mathbf{z}'_k \mathbf{z}'_k{}^T, \quad (26)$$

$$\hat{\mathbf{m}}_{eq} = \frac{1}{P} \sum_{k=0}^{P-1} b'_k \mathbf{z}'_k. \quad (27)$$

Note that the number of taps L_c is odd number, because we use the general equalizer [15].

5. Computational Complexity

The complexity of the receiver depends on the specific algorithms, the hardware architectures, and the other factors. In this paper, we consider the computational complexities of MRC-RAKE, MMSE-RAKE, and MRC-RAKE-Equalizer. The computational complexities of the RAKE receivers depend on the derivation methods of the finger or tap weights and the number of fingers, taps, and pilot symbols. The BER of MRC-RAKE is inferior to that of MMSE-RAKE, however, the computational complexity of MRC-RAKE is

Table 1 The number of multiplication and addition in weight derivation for each receiver ($L_p = 10$, $L_c = 9$).

P	Complexity	MRC	MMSE	MRC+Equalizer
20	multi*	210	3410	2910
	add*	190	3180	2701
50	multi	510	6710	5910
	add	490	6480	5701
100	multi	1010	12210	10910
	add	990	11980	10701
500	multi	5010	56210	50910
	add	4990	55980	50701

multi* = multiplication, add* = addition

Table 2 The computational complexity for each receiver.

Receiver	L_p	$P = 20$	$P = 50$	$P = 100$	$P = 500$
MRC-RAKE	30	1380	2280	3780	15780
MMSE-RAKE	10	3660	6960	12460	56460
	20	17410	30010	51010	219010
MRC-RAKE -Equalizer ($L_c = 9$)	10	3169	6169	11169	51169
	20	3629	6929	12429	56429
	30	4080	7689	13689	61689

lower than that of MMSE-RAKE. That is, there is a trade-off between the BER and the computational complexity. The multiplication and the addition are dominant in the computational complexity [12], [13]. For example, the order of calculation of the matrix inversion with the size of matrix N is $O(N^3)$ for both the multiplication and the addition, and that of the multiplication of the $\{N \times M\}$ matrix and the $\{M \times N\}$ matrix are $O(MN^2)$ for the multiplication and $O((M-1)N^2)$ for the addition [12]. The main issue is to give an overall idea of how the sizes of various parameters influence the computational complexity. Table 1 shows the number of both the multiplication and the addition for the derivation of the finger and/or tap weights of the RAKE receivers with the number of fingers $L_p = 10$ and taps $L_c = 9$. We can see that the numbers of multiplication and addition of each receiver are almost equal. Consequently, we consider only the number of multiplication as same as [13].

Table 2 shows the number of all the multiplication per one symbol for each RAKE receiver. In the derivation of the computational complexity, we consider all the multiplication in the demodulation, the derivation of the finger or tap weights, and the RAKE combining. In Table 2, we can see that the computational complexities of MMSE-RAKE with $L_p = 10$ and MRC-RAKE-Equalizer with $L_p = 20$ and $L_c = 9$ are almost equal. This is because the computational complexity of MRC-RAKE is extremely low for the same number of fingers. We can also see that the computational complexity of each receiver is affected by the number of fingers and taps significantly. Note that the number of pilot symbols P affects the throughput significantly. Therefore, it is important to minimize the number of pilot symbols P with keeping the accuracy of channel estimation.

6. Simulation Results

In this section, we evaluate the BERs of MRC-RAKE,

Table 3 Simulation parameters.

System	DS-UWB
Number of pilot symbols	$P = 20, 50, 100, 500$
Number of fingers	$L_p = 10, 15, 20, 30$
Number of taps	$L_c = 9$
Transmission rate	$R_b = 250$ Mbps
Frame length	$T_f = 4$ ns
Chip width	$T_c = 0.167$ ns
Modulation	BPSK
Channel model	IEEE 802.15.SG3a UWB Multipath channel model [4]

Table 4 An example of ternary codes with $N_c = 24$.

number	code sets
1	-1 1 -1 -1 1 -1 -1 1 -1 0 -1 0 -1 -1 1 1 -1 1 1 -1 -1 -1 -1
2	0 -1 -1 0 1 -1 -1 1 -1 -1 1 1 1 -1 -1 1 -1 -1 1 1 1 1 1
3	-1 -1 -1 -1 1 -1 1 -1 -1 -1 -1 -1 -1 1 -1 -1 1 1 0 -1 0 1 1
4	0 -1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 -1 1 -1 1 -1 -1 1 -1

MMSE-RAKE, and MRC-RAKE-Equalizer with considering the accuracy of channel estimation in DS-UWB by computer simulation.

6.1 Parameter Setting

Table 3 shows the parameters used in our simulation. We select the Ternary code of the sequence length $N_c = 24$ for Direct Sequence (DS) system, as well as the DS-UWB system proposed in IEEE standardization [2] and employ the 2-ary Biphase Orthogonal Keying (2BOK) that allocates the sequence according to the input data bit modulated by BPSK. Table 4 shows an example of Ternary codes with $N_c = 24$. In our simulation, we select the code of the number 1 and define the energy per symbol $E_s = (N_c - 2)E_c$ with considering zero components in the ternary codes. We also consider the single user scenario and employ the CM (Channel Model) 3 in IEEE 802.15.3a UWB multipath channel model [4]. It is a non-line-of sight environment. In CM 3, the distance between the transmitter and the receiver is assumed to be 4–10 m and the RMS delay spread is assumed to be 14.28 ns. Figure 3 shows the propagation model for CM 3. We can see that the UWB channel has a significant number of multipath components that have different delays of the order of nanosecond. Note that the number of total paths L_{tot} is different every channel realization. In our simulation, we assume that the receiver knows the total number of paths L_{tot} (i.e. $L_{est} = L_{tot}$) [11]. In practice, L_{tot} is about 1000–1300.

The number of fingers L_p of the RAKE receiver must be selected with considering the multipath length of channel, performance, and complexity. In general, when the channel estimation is perfect or the accuracy of channel estimation is high, L_p is set to 60 from the characteristic of CM 3 [5], [6]. In contrast, when the accuracy of channel estimation is low, L_p is set smaller than 60, because the use of RAKE receiver with many fingers degrades the performance with channel estimation error. In this paper, we set $L_p = 10, 20, 30$ with considering the computational complexity of the receiver and the accuracy of channel estimation.

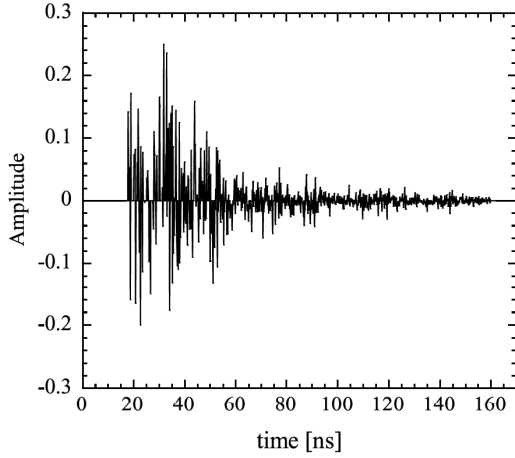


Fig. 3 UWB multipath channel: CM 3.

tion and facilitating the simulation.

The number of taps L_c of the equalizer must be selected based on ISI, because the UWB multipath is spread over dozens of symbols in the case of ultra high-speed communications. In CM 3, since the maximum delay spread is about 210 ns, the number of taps L_c needed to remove ISI effectively is about $L_c = 50$ because the frame length T_f is 4 ns. Thus, if the channel estimation is perfect or the accuracy of channel estimation is high, the equalizer with $L_c = 50$ can achieve good performance. However, $L_c = 50$ leads to the high computational complexity. Therefore, in the range in which the simulation is possible, the number of taps L_c in MRC-RAKE-Equalizer that results in the same computational complexity as MMSE-RAKE with $L_p = 10, 20$ is about $L_c = 9, 19$ with considering the computational complexities of MRC-RAKE part and MMSE equalizer. In this paper, we select $L_c = 9$ for the equalizer so that we can evaluate the performance by computer simulation and compare the performance of each receiver at the same computational complexity. Thus, MRC-RAKE-Equalizer ($L_p = 20$) and MMSE-RAKE ($L_p = 10$) have almost the same computational complexity.

6.2 MSE and BER Performances

Figure 4 shows the MSE between the desired channel impulse response and the estimates of that. We can see that as the number of pilot symbols P increases, the MSE of the channel estimation is improved. In this paper, we employ $P = 100, 500$ for the case of the high accuracy of channel estimation and $P = 20, 50$ for the case of the low accuracy of channel estimation.

Figures 5 and 6 show the BERs of MRC-RAKE with $L_p = 30$, MMSE-RAKE with $L_p = 10, 20$, and MRC-RAKE-Equalizer with $L_p = 10, 20, 30$ and $L_c = 9$ for $P = 100, 500$, respectively. As shown in Table 2, the computational complexities of MMSE-RAKE with $L_p = 10$ and MRC-RAKE-Equalizer with $L_p = 20$ and $L_c = 9$ are al-

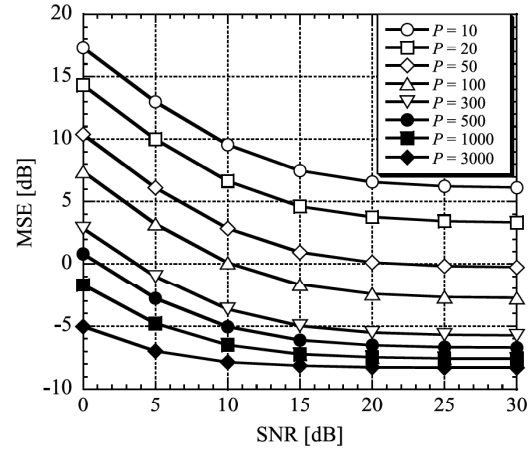
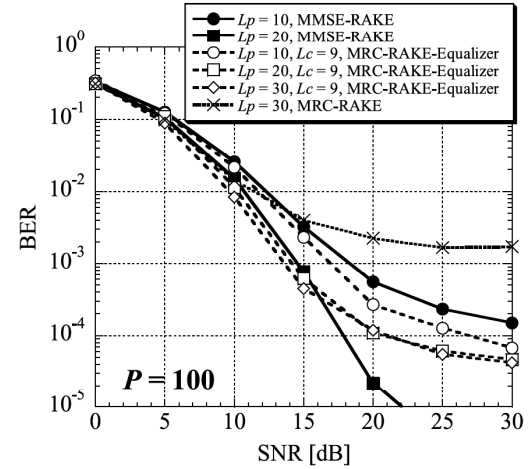


Fig. 4 The MSE of the channel estimation.

Fig. 5 The BER vs. the SNR: $P = 100$, MRC-RAKE ($L_p = 30$), MMSE-RAKE ($L_p = 10, 20$), and MRC-RAKE-Equalizer ($L_p = 10, 20, 30, L_c = 9$).

most identical for $P = 100, 500$, respectively. The computational complexity of MMSE-RAKE with $L_p = 20$ is approximately quadruple, compared to that of MMSE-RAKE with $L_p = 10$, for $P = 100, 500$, respectively. We can see that MRC-RAKE-Equalizer with $L_p = 10, 20, 30$ and $L_c = 9$ achieves the better BER than MMSE-RAKE with $L_p = 10$, for $P = 100, 500$, respectively. In addition, compared to the BER of MMSE-RAKE with $L_p = 20$ that has the high computational complexity, MRC-RAKE-Equalizer with $L_p = 20, 30$ for $P = 100, 500$ achieves the good BER at the low SNR. In particular, MRC-RAKE-Equalizer with $L_p = 30$ and $P = 500$ has about 2 dB advantage at the BER $= 10^{-4}$, compared to MMSE-RAKE with $L_p = 20, P = 500$.

On the other hand, we can see that there exists the high error floor on the BER of MRC-RAKE with $L_p = 30$ for $P = 100, 500$. This is because the weights of MRC-RAKE are the channel gains of the paths and because MRC-RAKE

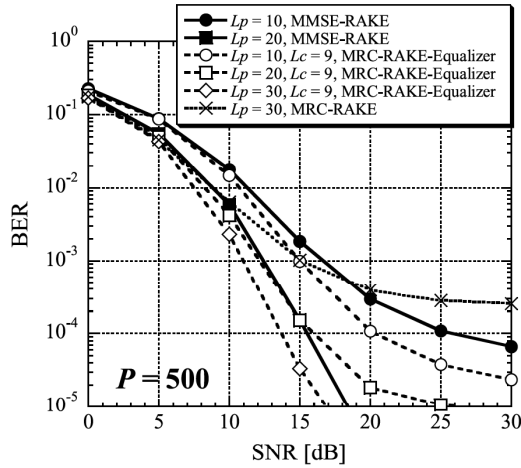


Fig. 6 The BER vs. the SNR: $P = 500$, MRC-RAKE ($L_p = 30$), MMSE-RAKE ($L_p = 10, 20$), and MRC-RAKE-Equalizer ($L_p = 10, 20, 30, L_c = 9$).

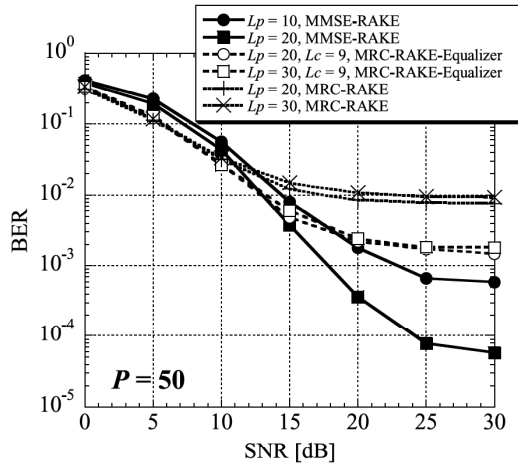


Fig. 7 The BER vs. the SNR: $P = 50$, MRC-RAKE ($L_p = 20, 30$), MMSE-RAKE ($L_p = 10, 20$), and MRC-RAKE-Equalizer ($L_p = 20, 30, L_c = 9$).

enhances ISI in the RAKE combining. Correspondingly, MRC-RAKE-Equalizer with $L_p = 10, 20, 30$ and $L_c = 9$ for $P = 100, 500$ achieves the better BER than MRC-RAKE with $L_p = 30$. This is because the residual ISI components are removed by employing MMSE-Equalizer with $L_c = 9$.

Figures 7 and 8 show the BERs of MRC-RAKE with $L_p = 20, 30$, MMSE-RAKE with $L_p = 10, 15, 20$, and MRC-RAKE-Equalizer with $L_p = 20, 30$ and $L_c = 9$ for $P = 20, 50$, respectively. As shown in Table 2, the computational complexities of MMSE-RAKE with $L_p = 10$ and MRC-RAKE-Equalizer with $L_p = 20$ and $L_c = 9$ are almost identical for $P = 20, 50$, respectively. The computational complexity of MMSE-RAKE with $L_p = 20$ is approximately five times, compared to that of MMSE-RAKE with $L_p = 10$, for $P = 20, 50$, respectively. The reduction of the

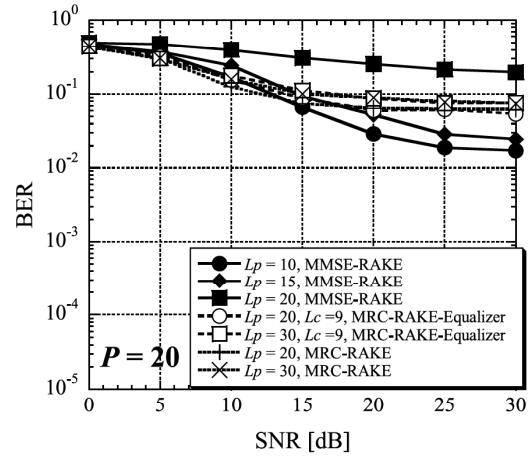


Fig. 8 The BER vs. the SNR: $P = 20$, MRC-RAKE ($L_p = 20, 30$), MMSE-RAKE ($L_p = 10, 15, 20$), and MRC-RAKE-Equalizer ($L_p = 20, 30, L_c = 9$).

number of pilot symbols P consequently leads to the degradation of the accuracy of channel estimation. In particular, the accuracy of channel estimation with $P = 20$ is significantly low. In Figs. 7 and 8, we can see that the BER of each receiver for $P = 20, 50$ degrades significantly, compared to that of each receiver for $P = 100, 500$. We can also see that MMSE-RAKE with $L_p = 10$ achieves the better BER than MRC-RAKE-Equalizer at high SNR with $L_p = 20, 30$ and $L_c = 9$, for $P = 20, 50$, respectively. When the accuracy of channel estimation is low, the effect of the Equalizer in MRC-RAKE-Equalizer is low. This is because MRC-RAKE-Equalizer uses MRC-RAKE that yields the high error floor. In Fig. 8, there is no effect of the Equalizer for this reason. On the other hand, each receiver with the small number of fingers achieves the better BER than that with the large number of fingers. In particular, the BER of MMSE-RAKE degrades significantly as the number of fingers increases, compared to that of MRC-RAKE. When the accuracy of channel estimation is significantly low, the channel estimation error is significantly large. Thus, in the RAKE combining, the larger the number of fingers becomes, the larger the effects of the channel estimation error becomes. In addition, it is difficult for each RAKE receiver to select the optimum paths when the accuracy of channel estimation is significantly low. In the derivation of the weights of MMSE-RAKE, the channel estimation error is enhanced significantly as the number of fingers increases, because that uses the correlation matrix based on the selected paths and the estimates of path gains. For this reason, when the accuracy of channel estimation is significantly low, the BER sensitivity of MMSE-RAKE is higher than that of MRC-RAKE.

7. Comparison

In this section, we summarise the performance of each re-

ceiver from our simulation results in Figs. 5–8.

- **MRC-RAKE**

The computational complexity of MRC-RAKE is very low, and MRC-RAKE can capture a large signal energy with using a large number of fingers. However, MRC-RAKE needs high accuracy of channel estimation. When the accuracy of channel estimation is low, the channel estimation error degrades the performance of MRC-RAKE with a large number of fingers, as shown in Figs. 7 and 8. In addition, MRC-RAKE can not remove ISI. Thus, there exist an floor on BER of MRC-RAKE in Figs. 5–8.

- **MMSE-RAKE**

MMSE-RAKE can achieve good BER so that it can remove ISI in the received signal path selected by each finger. The number of fingers of MMSE-RAKE needs to be set with considering trade-off between performance and complexity, because the computational complexity of MMSE-RAKE increases significantly with the number of fingers. In addition, the effect of channel estimation error is small compared to MRC-RAKE. When the accuracy of channel estimation is low, MMSE-RAKE can achieve the best performance in each receiver, as shown in Figs. 7 and 8.

- **MRC-RAKE-Equalizer**

MRC-RAKE-Equalizer can achieve good BER by capturing a large signal energy in MRC-RAKE and removing ISI symbol by symbol in MMSE-Equalizer. In particular, when the accuracy of channel estimation is high as in Figs. 5 and 6, MRC-RAKE-Equalizer can achieve good BER with low computational complexity. Comparing MMSE-RAKE with $L_p = 10$ to MRC-RAKE-Equalizer with $L_p = 20$, $L_c = 9$, the effect of removing ISI by MMSE-RAKE is thought to be higher than that by Equalizer, because L_p is larger than L_c . However, as shown Figs. 5 and 6, MRC-RAKE-Equalizer can achieve better BER than MMSE-RAKE. This is because MRC-RAKE-Equalizer can capture a large signal energy using MRC-RAKE with many fingers. While, when the accuracy of channel estimation is low as in Figs. 7 and 8, the performance of MRC-RAKE-Equalizer degrades compared to MMSE-RAKE, because MRC-RAKE can not capture large signal energy and because the effect of removing ISI is low compared to MMSE-RAKE.

8. Conclusions

In this paper, we have evaluated the computational complexities and the BERs of MRC-RAKE, MMSE-RAKE, and MRC-RAKE-Equalizer with considering the accuracy of channel estimation for DS-UWB. We showed that the computational complexity of MRC-RAKE is extremely lower than those of MMSE-RAKE and MRC-RAKE-Equalizer. We also showed that the computational complexities of MMSE-RAKE with $L_p = 10$ and MRC-RAKE-Equalizer

with $L_p = 20$, $L_c = 9$ are almost equal for $P = 20, 50, 100, 500$. From the results of our simulation, we showed that the accuracy of channel estimation affects the BERs of MRC-RAKE, MMSE-RAKE, and MRC-RAKE-Equalizer significantly. We also showed that when the accuracy of channel estimation is high such as $P = 100, 500$, MRC-RAKE-Equalizer can achieve the better BER than MMSE-RAKE with less computational complexity and when the accuracy of channel estimation is low such as $P = 20, 50$, MMSE-RAKE can achieve the better BER than MRC-RAKE-Equalizer. Moreover, we showed that when the accuracy of channel estimation is significantly low such as $P = 20$, the BER of each receiver degrades significantly as the number of fingers increases.

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