Adaptive MMSE Rake-Equalizer Receiver Design with Channel Estimation for DS-UWB System

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Abstract: - In this paper, a robust adaptive MMSE Rake-equalizer receiver scheme is presented with channel estimation that has been transmitted in Direct Sequence-Ultra Wideband (DS-UWB) system. The DS-UWB has a fine path resolution by transmitting information with ultra short pulses. The Rake receiver is known as a technique that can effectively combine paths with different delays and obtain the path diversity gain. Due to sub-nano seconds narrow pulse and the large transmission bandwidth in the systems, we therefore use equalizer to overcome the resulting ISI and a long delay spread in the characterization of the UWB channel. The proposed receiver structure reduces intense multi-path destruction and severe inter-symbol interference (ISI) by using a combined adaptive Rake and equalizer structure referred to as the MMSE (minimum mean square error) algorithm. Channel information is obtained through the use of a least mean square (LMS) adaptive algorithm on the training sequence of a preamble. The indoor environment is represented by dense multipath channel models proposed by IEEE 802.15.3a. Simulation results show that the new scheme employing the energy of a few paths to obtain better performance than the traditional maximum ratio combining (MRC) Rake receiver.

Key-Words: - Least mean squares (LMS), minimum mean square error (MMSE), adaptive receiver, direct sequence ultra wideband (DS-UWB)

1. Introduction

Direct Sequence-Ultra Wideband (DS-UWB) offers great potential in terms of low power, enhanced user capacity, high data rates and ability to coexist with legacy services. Most of these benefits originate from the unique characteristics inherent to UWB wireless transmissions [1]. The UWB systems spread the energy from several hundred MHz to a few GHz [2]. The received signal is composed of a significant number of multipath components that have different delays on the order of nanoseconds. The UWB has a fine path resolution by transmitting information with ultra short pulses. The Rake receiver is known to be a technique that can effectively combine paths with different delays and obtain the path diversity gain [3]. However, the UWB multipath channel is spread over dozens of symbols in the case of ultra high-speed communications of several hundreds Mbps, which results in a strong frequency selective channel [4]. Consequently, the Rake receiver needs a large number of fingers and the computational complexity of the Rake receiver becomes high [5]. In addition, the Rake receiver must estimate a large number of channel impulse responses, thus computational complexity of channel estimation is very high. The conventional Rake receiver employs the weight vector to perform the maximal ratio combining (MRC) which maximizes the output signal-to-noise ratio (SNR) when the interference is modeled as additive white Gaussian noise [6]. But for its complexity and cost to remain low, the number of fingers that can be afforded is too small to capture the ample energy provided by the UWB channel, which entails a large number of paths (often>50) [7]. In the presence of narrowband interference, the bit error rate preference of an UWB MRC Rake receiver exhibits an error floor. A more effective receiver scheme is the minimum mean square error (MMSE) Rake receiver [8] which achieves a much improved performance for WCDMA system. Meanwhile, due to sub-nano seconds narrow pulse and the large transmission bandwidth in the UWB system, the equalizer has also recently attracted much attention [9] as a means to overcome the resulting inter-symbol interference (ISI) and a long delay spread in the characterization of the UWB channel. It is reported that the equalizer can obtain an excellent performance even in strong frequency selective channels [10] which assume in perfect channel environment. Combination of spatial diversity combining and equalizer is a well established scheme for frequency selective fading channels. However, like any Rake structure, it needs the complete channel state information. Furthermore, the performance evaluation of UWB systems over a multipath fading channel is always conducted under the assumption of perfect channel estimation [11].

The inaccurate channel estimation [12] would lead to a serious degradation of BER performance. The method was proposed in [13] to estimate channel and equalizer design in frequency domain and it requires extra FFT calculations.

In this paper, we introduce a robust receiver design incorporating a channel estimation scheme for DS-UWB over a realistic indoor multipath channel. The proposed receiver reduces intense multi-path destruction and severe ISI by using a combined adaptive Rake and equalizer structure referred to as the adaptive MMSE Rake-equalizer receiver. Relevant receiver parameters are estimated using the MMSE algorithm. This has motivated studies of multipath combining receivers that process only a subset of the available L_p resolved multipath components. We obtain more robust signal detection at the receiver side by the adaptive channel estimation in order to extract more accurate channel state information. The channel characteristics are first estimated using the LMS adaptive algorithm on the training sequence of the preamble. The proposed receiver is able to employ the energy of a few paths and obtain better performance by the proposed receiver design. The performance of the adaptive MMSE Rake-equalizer structure for DS-UWB system is investigated for different number of Rake fingers and equalizer taps.

The remainder of the paper is organized as follows. Section II briefly describes the proposed DS-UWB system model including transmitter, UWB indoor channel model and adaptive receiver structure. In Section III, an adaptive MMSE Rake-equalizer is proposed conjunction with an LMS channel estimator. Section IV investigates the performance of the proposed method and compares it with the traditional approach. Finally, some concluding remarks are given in Section V.

2. System Model

We show the transmitter and receiver structure for DS-UWB in Fig. 1. The data symbol sequence modulated by BPSK is first spread using the spreading code. The transmitted signal of the considered DS-UWB system is given by

$$s(t)=\sum_{n=1}^{\infty} b_n w(t-nT_s) \qquad (1)$$

where $b_n \in \{\pm 1\}$ is the n^{th} transmit data symbol, T_s is the symbol duration and the spreading waveform $w(t)$ is expressed as

$$w(t)=\sum_{m=1}^{M} c_m p(t-mT_c), \qquad (2)$$

where c_m denotes the m^{th} chip of the spreading code of length M and T_c is chip duration ($T_s=MT_c$). The chip pulse $p(t)$ represents the monocycle waveform normalized to have unit energy and the spreading code is defined in the DS-UWB specification [14].

In this paper, each DS-UWB is evaluated using the UWB multipath channel model based on the indoor channel measurements in the 2-8GHz frequency band accepted by the IEEE 802.15-SG3a standard [15]. The UWB indoor channel model adopts a double-exponential decay intensity profile based on the Saleh-Valenuela model. It provides enough degrees of freedom to match channel measurements, and can be used to match the NLOS and LOS channel characteristics separately. The multipath model consists of the following discrete time impulse response:

$$h(t)=\sum_{l=0}^{L_T}\sum_{k=0}^{K}\alpha_{k,l}\delta(t-T_l-\tau_{k,l}) \qquad (3)$$

where $\alpha_{k,l}$ is the real multipath gain coefficient, T_l is the delay of the l^{th} cluster, and $\tau_{k,l}$ is the delay of the k^{th} multipath component of the l^{th} cluster arrival time (T_l). L_T is the total number of clusters and K is the total number of ray paths relative to the l^{th} cluster. The channel coefficients can be expressed as $\alpha_{k,l}=p_{k,l}\beta_{k,l}$, where $p_{k,l}$ is equally likely to take on the values of ± 1, and $\beta_{k,l}$ is the lognormal fading term. The distribution of cluster arrival time and the ray arrival time are given by

$$p\left(T_l \middle| T_{l-1}\right)=\Lambda\exp\left[-\Lambda\left(T_l-T_{l-1}\right)\right], \quad l>0$$

$$p\left(\tau_{k,l} \middle| \tau_{(k-1),l}\right)=\lambda\exp\left[-\lambda\left(\tau_{k,l}-\tau_{(k-1),l}\right)\right], \quad k>0$$

The channel coefficients are defined as follows:

$$20\log 10(\beta_{k,l}) \propto \mathrm{Normal}(\mu_{k,l},\sigma^2)$$

$$E\left[\beta_{k,l}^2\right]=\Omega_0 e^{-T_l/\Gamma}e^{-\tau_{k,l}/\gamma}$$

$$\mu_l=\frac{10\ln(\Omega_0)-10T_l/\Gamma-10\tau_{k,l}/\gamma}{\ln(10)}-\frac{\sigma^2\ln(10)}{20}$$

respectively, where

$\tau_{k,l}$ = the mean power of the first path of the first cluster

T_l= the arrival time of the first path of the lth cluster;

$\tau_{k,l}$ = the delay of the kth path within the lth cluster relative to the first path arrival time, T_l

Λ = cluster arrival rate;

λ = ray arrival rate, i.e., the arrival rate of path within each cluster.

Γ = cluster decay factor;

γ = ray decay factor;

σ =standard deviation of lognormal fading (dB).

Table 1 lists an example of these key parameters for four different channel models. The above results assume that the UWB channel model fits the measurements taken in the home environment for both LOS and NLOS cases. In this study, the channel model parameters have matched the UWB channel measurements with a typical rms delay spread of 15-20*ns*. The channel coefficients are normalized to remove the effect of path loss for the UWB channel model.

Hence, the received signal, $r(t)$, at the receiver's input is given by

$$r(t) = \sum_{n=1}^{\infty}\sum_{l=0}^{L_T}\sum_{k=0}^{K} b_n \alpha_{k,l} w(t - nT_s - T_l - \tau_{k,l}) + u(t) \tag{4}$$

where $u(t)$ is the additive white Gaussian noise (AWGN) with two sided power spectral density $N_0/2$. In general, a receiver structure consists of *L* correlators followed by a Rake combiner. Each correlator correlates the received signal with the reference waveform at the delay time and integrates over T_s.

3. Channel Estimation and Adaptive MMSE Rake-Equalizer Receiver

The proposed receiver structure for DS-UWB system is as shown in Fig. 2. In this section, the proposed receiver reduces intense multi-path destruction and severe ISI by using a combined adaptive Rake and equalizer structure referred to as the adaptive MMSE Rake-equalizer receiver. Due to the large transmission bandwidth, the UWB channel is characterized by a long root-mean square delay spread and the Rake receiver cannot always overcome the resulting ISI [16]. We therefore study equalization for DS-UWB systems. The channel characteristics are first estimated using the LMS adaptive algorithm and initial value by the training sequence of preamble. The structure of the preamble is shown in Table 2. An adaptive receiver structure and channel estimation for DS-UWB system is investigated, which can improve the performance of bit error rate.

A. Channel estimation by using LMS adaptive algorithm

Equation (4) can be written as

$$r(t) = \sum_{n=1}^{\infty} b_n \cdot g(t - nT_s) + u(t) \tag{5}$$

where $g(t) = w(t) * h(t)$ (6)

We employ the LMS adaptive algorithm to perform the channel estimation. We assume the known training sequence $\mathbf{b} = [b_1, b_2, \cdots b_P]$ including *p* bit and channel attenuations in DS-UWB system to be estimated into a matrix **g**. A fading channel with *L* resolvable paths is considered and the received signal at time *n* shown into a vector $\mathbf{r}_P$. Let us define matrix $\tilde{\mathbf{g}} = [\mathbf{g}_{p,1}, \mathbf{g}_{p,2}, \cdots, \mathbf{g}_{p,L}]$ of size $(P \times L)$ where $\mathbf{g}_{p,1}$ (*p*=1,2,…,*P*) is the first column vector. At the first iteration, the initial channel estimation, $\tilde{\mathbf{g}}$, which contains channel information, is based only upon training sequences that were computed. The linear least square channel estimation [17] can be estimated by the Gauss-Markov theorem given by:

$$\tilde{\mathbf{g}} = \mathbf{b}^H \cdot \mathbf{r}_P \tag{7}$$

where $\mathbf{r}_P = [r_1(n), r_2(n), \cdots, r_L(n)]$ and

$$\tilde{\mathbf{g}} = \begin{bmatrix} g_{1,1} & g_{1,2} & \cdots & g_{1,L} \\ g_{2,1} & g_{2,2} & \cdots & g_{2,L} \\ \vdots & \vdots & \ddots & \vdots \\ g_{P,1} & g_{P,2} & \cdots & g_{P,L} \end{bmatrix}_{P \times L}$$

The adaptive channel estimation based on LMS algorithm involves three basic iterative steps:

Step1: Filtering

$$\tilde{\mathbf{b}}^{(n)} = \mathbf{r}_P^{(n)} (\tilde{\mathbf{g}}^H)^{(n)} \tag{8}$$

Step2: Computing estimation error

$$\mathbf{e}^{(n)} = \mathbf{b}^H - (\tilde{\mathbf{b}}^H)^{(n)} \tag{9}$$

Step3: Adaptive weight adjustment

$$\begin{aligned} \tilde{\mathbf{g}}^{(n+1)} &= \tilde{\mathbf{g}}^{(n)} - \mu_c^{(n)} \nabla^{(n)} = \tilde{\mathbf{g}}^{(n)} - \mu_c^{(n)} \frac{\partial}{\partial \tilde{\mathbf{b}}^{(n)}} \mathbf{E}[|\mathbf{e}^{(n)}|^2] \\ &= \tilde{\mathbf{g}}^{(n)} + \mu_c^{(n)} \mathbf{e}^{(n)} (\mathbf{r}_p)^{(n)} \end{aligned} \tag{10}$$

where (*n*) represents the time step in the iterative process, μ_c is the positive step-size parameter, ∇ is the gradient of $\mathbf{E}[|\mathbf{e}^{(n)}|^2]$ and the superscript H represents Hermitian transpose. Note that $|\mathbf{e}^{(n)}|^2$ itself is a very noisy approximation to $\mathbf{E}[|\mathbf{e}^{(n)}|^2]$. We can get a noisy approximation to the gradient by finding the gradient of $\mathbf{E}[|\mathbf{e}^{(n)}|^2]$ (Hoff first published the LMS algorithm based on this clever idea, in 1960.) By means of the self-optimizing technique [18], we can derive the optimum step-size parameter $[\mu_c^{(n)}]_{opt} = 1/\|\mathbf{r}_p\|^2$, which is time-varying and inversely proportional to instantaneous power of the channel estimator's input signal. Thus adaptive weight adjustment with the optimum step-size parameter is:

$$\mathbf{g}^{(n+1)} = \mathbf{g}^{(n)} + \mathbf{e}^{(n)} \cdot (\mathbf{r}_p)^{(n)} / \| \mathbf{r}_p \|^2 \qquad (11)$$

Therefore, $\mathbf{g}$ can be estimated at the iterative process in matrix form as $\tilde{\mathbf{g}} = [\mathbf{g}_{p,1}, \mathbf{g}_{p,2}, \cdots, \mathbf{g}_{p,L}]$, which contains channel information (The amplitudes and delays are incorporated).

B. Adaptive MMSE Rake-Receiver Weight Estimation

The weights of the traditional Rake receiver are $\tilde{\boldsymbol{\beta}}^H = [\boldsymbol{\beta}_1, \boldsymbol{\beta}_2, \cdots, \boldsymbol{\beta}_L]^H = [\mathbf{g}_{p,L}, \mathbf{g}_{p,L-1} \cdots, \mathbf{g}_{p,1}]^H$. The proposed adaptive MMSE Rake receiver in Fig. 3 is composed of a Rake combine with L fingers to collect signal energy and mitigate ISI and other interference. The adaptive rake structure attempts to utilize mulipath diversity in the same style as the rake receiver on each finger. Minimising the cost function $\xi = \mathbf{E}\{|e[n]|^2\}$ results in each component acquiring information on how to improve the final estimate $\tilde{I}[n]$ taking all input samples into account. The weight coefficients of the L taps for the MMSE filter are chosen as to minimize the MSE between the desired output and the received output at each finger.

The weight vector $\tilde{\boldsymbol{\beta}}$ contains all of the filter coefficients and the receiver vector $\mathbf{r} = [r_1[n], r_2[n], \cdots r_L[n]]$ contains all the filter input samples. Assuming the perfect synchronization between the transmitter and the receiver, the lth correlator output $r_l[n]$ (l= 1,2,…L) for the nth desired data symbol.

The output $\tilde{I}[n]$ of the Rake-Receiver system and update equations are consequently as follows.

$$\tilde{I}[n]^{(n)} = \mathbf{r}^{(n)} (\tilde{\boldsymbol{\beta}}^H)^{(n)} \qquad (12)$$

$$e[n]^{(n)} = \tilde{I}[n]^{(n)} - d[n] \qquad (13)$$

$$(\tilde{\boldsymbol{\beta}}^H)^{(n+1)} = (\tilde{\boldsymbol{\beta}}^H)^{(n)} + \frac{(\mathbf{r}^H)^{(n)} e[n]^{(n)}}{|\mathbf{r}^{(n)}|^2} \qquad (14)$$

As with the MMSE receiver the filters are only required to compute an output and perform coefficient updates at symbol rate. The iterative scheme is presented to obtain more accurate performance, which can efficiently suppress the influence of noise component. If $e[n]^{(n)} < e[n]^{(n+1)}$, the iterative can be terminated and the final decision is available. The just as we see, the iteration operation is a key feature of our proposed system and much more precise receiver design can be achieved. It is nature to assume the more the iteration time is, the better the performance will be achieved. However, we will see through the simulation results that the performance improvement obtained by the iteration will appear saturate after some iteration.

C. MMSE Channel Equalizer Coefficients Estimation

Due to the tremendous high data rate and longer multipath delay spread as CM3 and CM4, the Rake receiver cannot always overcome the resulting ISI [19]. We therefore need to append equalizer for DS-UWB systems. In the MMSE Rake-equalizer receiver, the equalizer is used to mitigate residual interference. In this paper, assuming that the nth data bit is being detected, the MMSE criterion is to minimize $E[|b_n - \hat{b}[n]|^2]$. Let the number of equalizer taps be $2J$ and the coefficients of the equalizer be $\{c_{-J}, \cdots, c_J\}$. Then the equalizer output is

$$\hat{b}[n] = \sum_{j=-J}^{J} c_j \tilde{I}[n-j]. \qquad (15)$$

Let us define a vector **C** which contains all of the equalizer Coefficients and a vector **b** which contain all the

$$\varepsilon[n] = b_n - \hat{b}[n]$$

$$\hat{b}[n] = \sum_{j=-J}^{J} c_j \tilde{I}[n-j].$$

To optimize performance, the equalizer coefficients, $\tilde{\mathbf{c}} = [c_{-J}, \cdots, c_J]$, are chosen to minimize the MSE of its output, that is

$$\tilde{\mathbf{c}} = \arg\min_{\mathbf{c}} E[|b_n - \hat{b}[n]|^2] \qquad (16)$$

4. Simulations Results

UWB systems have a bandwidth exceeding 1GHz and satisfy the spectrum masking requirement of the FCC, the UWB pulse, or also known as the Gaussian monocycle waveform in [20], is chosen to be the 1^{th} derivative of the Gaussian function and it can be expressed as,

$$w(t) = -\frac{t - t_t}{\tau} e^{-\left(\frac{t-t_0}{\tau}\right)^2} \qquad (17)$$

where τ is a time constant for controlling the width of the pulse and is chosen according to the spectral mask requirement of the FCC and t_0 is a time offset. We evaluate the performance of DS-UWB with channel estimation and Rake receiver by computer simulation. The modulation format for DS-UWB is assumed to be BPSK with the spreading code of length 24. The transmitter pulse shaping has unit energy and the duration value for pulses transmitted is 0.7616 ns. We assume the perfect chip synchronization between the transmitter and the receiver. The characteristics of the convolutional encoder are such that its rate is 1/2 and constraint length is 6. The raw data rate is set to 28Mbps in the lower operating band. The receiver uses a training sequence length of 256 bits. Two different channel models (CM2 and CM4) were simulated using at least 100 channel realizations and the number of equalizer taps is $1\,(J=1)$.

Fig. 4 presents the bit error rate of the DS-UWB system based on the IEEE-UWB CM2 channel model for the perfect knowledge of the channel characteristics with different numbers of Rake fingers by varying the number of iterations. The proposed MMSE Rake-equalizer receiver performs quite well under the assumption of a perfect channel estimate and that the number of Rake fingers is 5 and 20. As indicated in Fig. 4, it is shown that the BER performance is improved by approximately 0.5dB after three iterations as compared with that of one.

Fig. 5 and Fig. 6 present the bit error-rate performances of the after three iteration of the proposed receiver and the MRC Rake receiver with perfect channel estimation for the cases of CM2 and CM4 channels respectively. It is clearly seen that performance improves with increasing number of Rake fingers since more energy is effectively used in the receiver as the number of Rake fingers increases. It is also seen that the MRC Rake receivers greatly underperforms the proposed iterative receiver under perfect channel estimation. In fig. 5, an adaptive MMSE Rake-equalizer receiver with number of Rake fingers L=5 performs as well as an MRC Rake receiver with number of Rake fingers L=20 over CM2 channel. In fig. 6, an adaptive MMSE Rake-equalizer receiver with number of Rake fingers L=5 outperforms an MRC Rake receiver with number of Rake fingers L=10 over CM4 channel.

Finally, Fig. 7 and Fig. 8 show the bit error rates of the DS-UWB system using the proposed iterative receiver with LMS channel estimation and assumed perfect channel estimation over CM2 and CM4 channels respectively. All detectors were implemented using the adaptive MMSE Rake-equalizer receivers with different numbers of fingers. It shows that the adaptive algorithm implemented can give a satisfactory performance. In practical receivers, however, it might not be viable to implement too many fingers in the Rake receiver.

5. Conclusions

In this paper, the performance of a robust MMSE Rake-equalizer receiver scheme in DS-UWB system is investigated for different number of Rake fingers and equalizer taps. The proposed receiver reduces intense multi-path destruction and severe ISI by using a combined adaptive Rake and equalizer structure referred to as the MMSE Rake-equalizer receiver. This paper studies a DS-UWB system that employs LMS channel estimation for canceling channel distortions subsequent to obtaining the channel information via a training sequence. The proposed receiver is able to employ the energy of a few paths and obtain better performance by the addition of a channel estimation scheme. The proposed receiver is a modified version of the conventional Rake receiver in which a Rake receiver with a simple equalizer is used to counteract the effects of the delay spread of UWB channels and the MMSE criterion is used to obtain the filter weights.

Simulation results show that channel estimation is necessary in a DS-UWB system. The proposed adaptive MMSE Rake-equalizer receiver enhances performance very well with an assumed perfect channel estimate. It is shown that increasing the number of Rake fingers is effective in improving system performance. We also show that DS-UWB with adaptive MMSE Rake-equalizer has better BER performance than DS-UWB with MRC Rake receiver, especially when the number of fingers is large. In particular it is shown that the performance of an adaptive MMSE Rake-equalizer receiver of number of Rake fingers equal to 5 (L=5) outperforms an MRC Rake receiver of number of Rake fingers equal to 10 (L=10) over CM4 channels. Finally, the LMS algorithm does give a satisfactory performance with fast convergence. In practical receivers it might not be able to implement too many fingers in the Rake receiver. The proposed adaptive MMSE Rake-equalizer receiver is able to employ the energy of a few paths and obtain better performance by the suitable receiver design. It shows that the adaptive algorithm gives a satisfactory performance.

References:

[1] L. Yang and G. B. Giannakis, “Ultra-wideband communications: an idea whose time has come,” *IEEE Signal Process. Mag.*, vol. 21, no. 6, pp. 26–54, Nov. 2004.

[2] M. Z. Win and R. A. Scholtz, “Ultra-wide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communications,” *IEEE Trans. on Comm.*, pp. 679–691, 2000.

[3] A. Rajeswaran, V. S. Somayazulu and J. R.

Foerster, “Rake performance for a pulse based UWB system in a realistic UWB indoor channel,” *International Conference on Communications*, vol. 4, pp. 2879–2883, May 2003.

[4] J. Foerster and Q. Li, "UWB channel modeling contribution from Intel," *IEEE P802.15-02/279-SG3a.*, Sept. 2002.

[5] Ning Xie and Yuanping Zhou, “An Adaptive Nonlinear Rake Receiver in UWB Wireless Communications,” *IEEE International Conference on Networking, Sensing and Control*, pp. 480-485, 23-25 April, 2006.

[6] H. Sheng, A. M. Haimovich, A. F. Molisch and J. Zhang, “Optimum Combining for Time Hopping Impulse Radio UWB Rake Receivers,” *IEEE Conference on Ultra Wideband Systems and Technologies*, pp. 224-228, Nov. 2003.

[7] Farahmand, S., Xiliang Luo and Giannakis, G.B., “Demodulation and tracking with dirty templates for UWB impulse radio: algorithms and performance,” *IEEE Transactions on Vehicular Technology*, vol. 54, pp. 1595 – 1608, Sept. 2005.

[8] G.W. Rice, D. Garcia-Alis, I. G. Stirling, S. Weiss and R. W. Stewart, “An Adaptive MMSE Rake Receiver,” *Asilomar Conference on SSC*, vol. 1, pp. 808-812, 29 Oct.-1 Nov. 2000.

[9] D. Falconer, S. L. Ariyavisitakul, A. B. Seeyar and B. Eidson, “Frequency domain equalization for single-carrier broadband wireless systems,” *IEEE Commun. Mag.*, pp. 58–66, 2002.

[10] M. Eslami and Xiaodai Dong, “Performance of Rake-MMSE-equalizer for UWB communications,” *IEEE WCNC*, vol.2, pp. 855 – 860, 13-17 March, 2005.

[11] J.F. Liao, C.L. Tsai and B.S. Chen, ”Robust adaptive channel estimation and multiuser detection for ultra wideband in a realistic indoor channel,” *International Conference on Communications*, 16-20 May, 2005.

[12] Y. Ishiyama and T. Ohtsuki, “Performance evaluation of UWB-IR and DS-UWB with MMSE-frequency domain equalization (FDE),” *IEEE Conf. on Globalcom*, pp. 3093–3097, Dec. 2004.

[13] H. Sato and T. Ohtsuki, “Frequency domain channel estimation and equalization for direct sequence ultra wideband (DS-UWB) system ,” *IEE proceedings communications*, vol. 153, pp. 93-98, Feb., 2006.

[14] IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs) “DS-UWB Physical Layer Submission to 802.15 Task Group 3a,” IEEE P802.15-04/0317r4, January, 2005.

[15] IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs) “UWB Channel Modeling Contribution from Intel,” IEEE P802.15-02/279r0-SG3a, 24 Nov., 2005.

[16] H. Niu, J. A. Ritcey and H. Liu, ”Performance of UWB Rake receivers with imperfect tap weights,” *IEEE Itnl. Conf. on Acoustic, Speech and Signal Processing*, vol. 4, pp. 125-128, April 2003.

[17] Hiroyuki SATO and Tomoaki OHTSUKI, **“**Computational Complexity and Performance of Rake Receivers with Channel Estimation for DS-UWB,” *IEICE Trans. Fundamentals*, pp. 2318-2326, 2005.

[18] X. Hou, S. Li, D. Liu, C. Yin and G. Yue, “On Two-Dimensional Adaptive Channel Estimation in OFDM Systems”, *IEE Proceedings Communications*, vol. 153, Oct. 2006.

[19] Ye Li, F. M. andreas and Jinyun Zhang, “Channel Estimation And Signal Detection for UWB”, A Mitsubishi Electric Research Laboratory, Nov. 2003.

[20] R. Dilmaghani, M. Hernandez and R. Kohno, “Optimum sequence design and performance evaluation of channel estimation techniques for UWB systems,” IEE Proc. Comm., pp 241 – 245, April 2005.

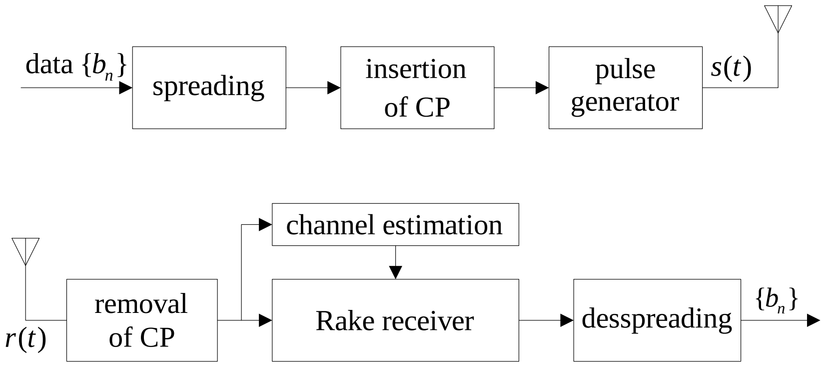

Fig.1 The transmitter and receiver structure for DS-UWB

Table 1 Multipath channel model parameters example.

Model Parameters	**CM 1 LOS(0-4m)**	**CM 2 NLOS(0-4m)**	**CM 3 NLOS(4-10m)**	**CM 4 Extreme NLOS**
Λ (1/nsec)	0.0233	0.4	0.0667	0.0667
λ (1/nsec)	2.5	0.5	2.1	2.1
Γ	7.1	5.5	14.00	24.00
γ	4.3	6.7	7.9	12
σ (dB)	3	3	3	3

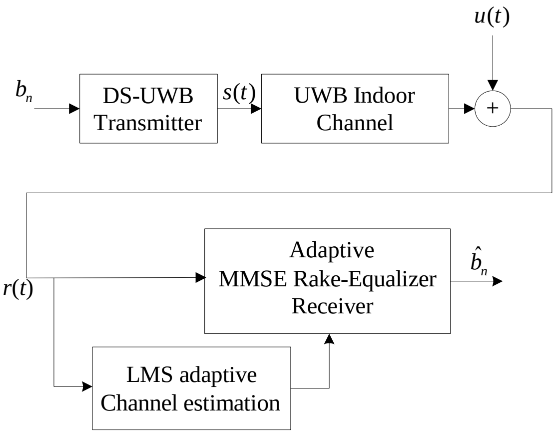

Fig. 2. The proposed receiver structure for DS-UWB system

Table 2 Structure of the general UWB preamble

Acq seq 9μs	SFD (32bit)	Data Field (24bit)	Training (various lengths)	PHY Header	MAC Header	Data

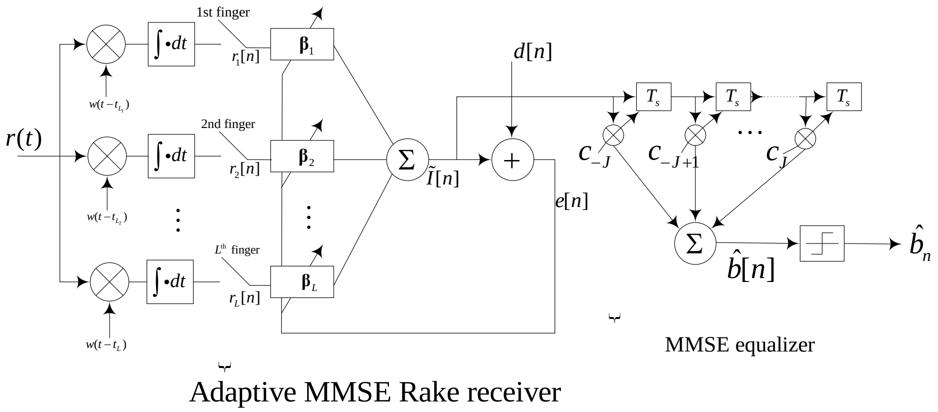

Fig. 3. The structures of the Adaptive MMSE Rake-equalizer receiver model.

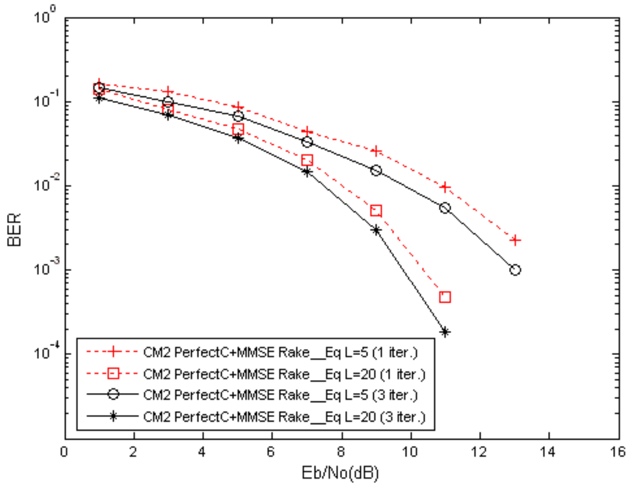

Fig. 4. Bit error rates of MMSE Rake-equalizer receiver with perfect channel estimation by varying the number of iterations for DS-UWB over CM2 channels

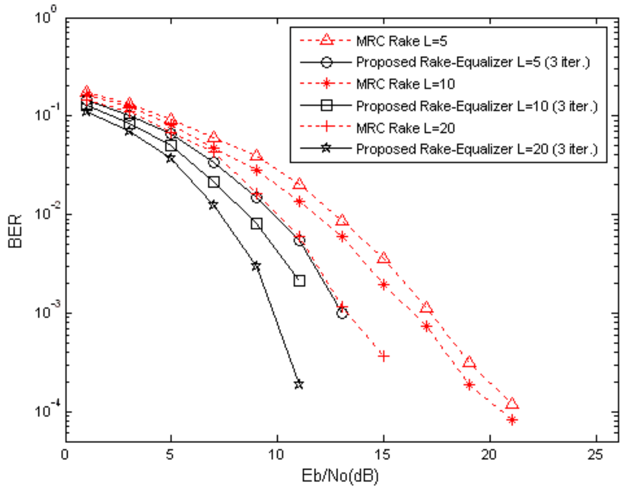

Fig. 5. Bit error rates of the proposed receiver and MRC Rake receiver with perfect channel estimation at different numbers of Rake fingers for DS-UWB over CM2 channels

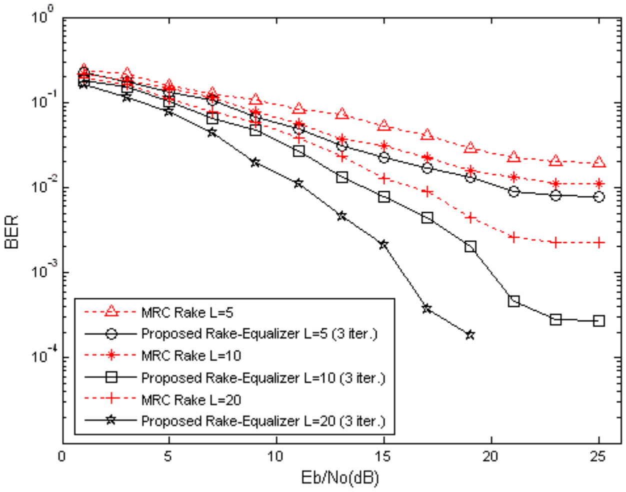

Fig. 6. Bit error rates of the proposed receiver and MRC Rake receiver with perfect channel estimation at different numbers of Rake fingers for DS-UWB over CM4 channels

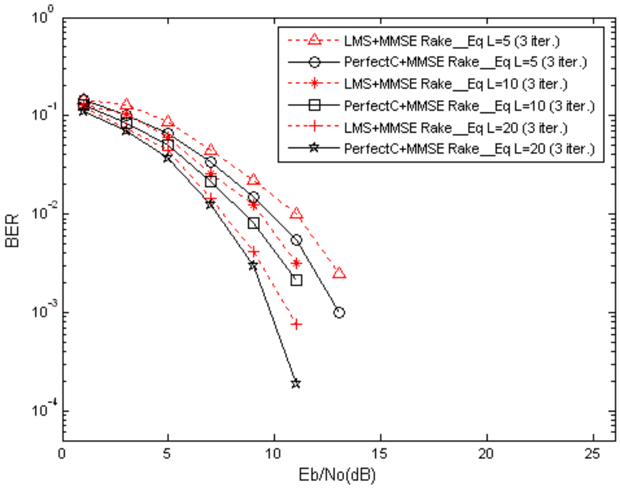

Fig. 7. Bit error rate of an proposed receiver using LMS channel estimation and that of an proposed receiver with assumed perfect channel estimation for different numbers of Rake fingers for DS-UWB over CM2 channels

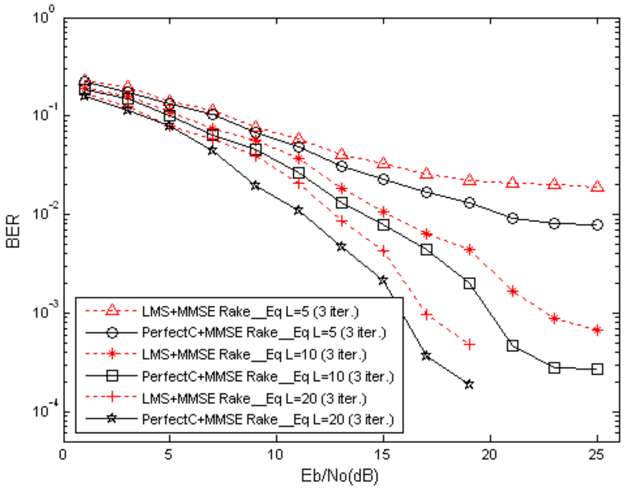

Fig. 8. Bit error rate of an proposed receiver using LMS channel estimation and that of an proposed receiver with assumed perfect channel estimation for different numbers of Rake fingers for DS-UWB over CM4 channels