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RESEARCH ARTICLE

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A less complicated adaptive equalization for UWB channels

Abstract In this paper, a new adaptive equalization scheme aiming at the intersymbol and interuser interferences in the multiuser ultra-wide band (UWB) channels is presented specially for direct-sequence UWB/time-hopping UWB (DS-UWB/TH-UWB) receivers. Its computational complexity and convergence rate are compared with the conventional algorithms. The simulation results show that the computational complexity of this scheme is less than employing the RLS method alone and the convergence rate of this scheme is farther off employing LMS method alone.

Keywords UWB receiver, channel characteristics, adaptive equalization, convergence, computational complexity

1 Introduction

In recent years, ultra-wideband (UWB) has attracted great interest of academic world, companies and manufacturers for its possible application in short distance multiuser indoor communication system. The application in this area has been researched and prospected in many papers [1–3]. In Ref. [1], the authors for the first time proposed the assumption of multiuser communication adopting impulse modulation, and the access capacity of multiuser in an ideal channel condition is further analyzed in Ref. [2]. In Ref. [3], the performance of an analog and digital UWB receiver is compared. However, because these analysis were made in an ideal scenario, there are still many difficulties both in theory and practice to be faced for the realization of UWB technology in wireless communication. One of the difficulties is how to correctly attain the signal severely distorted by the channel on the receiver. As we know, the fine time resolution of impulses for UWB can effectively improve the multipath decay and the extremely wide transmission bandwidth can enlarge the multiuser access capacity. However, it is not so perfect because an UWB communication system is mainly operated in the dense multipath indoor environment that brings many problems different from those in conventional narrowband channel. For example, owing to the different response to different frequency spectrum of UWB signal in the channel, the signal through the channel is severely distorted. Another example is that because of the effect of dense multipath, the signal energy is delayed and spread to each multipath component, which leads to the difficulty in realizing correct correlation receiving. The intersymbol and interuser interferences become drastically serious by multipath fading with the increase of data transmission rate and the number of access users. Simultaneously, the parameters of the channel change with the indoor environment, generally time-varying and nonlinear, and the channel characteristics are unknown before transmission. Therefore, how to improve the signal-to-noise ratio of the receiver to reduce the bit-error ratio in a multipath channel situation has become an open issue.

It is well known that the adaptive equalizer is an effective method to compensate the distortion caused by the change of channel parameters, which is mainly characterized by applying a certain rule-based adaptive algorithm to adjust the parameters of the equalizer in correspondence with the change of signal and channel to minimize the difference between the sending signal (training value) or the estimated value for output signal and the output signal of the equalizer. So the adaptive equalizer is usually used to overcome the intersymbol interference. In the multiuser UWB system, the features of UWB raise new requirements to the equalizing algorithm. One is the adaptive equalizing technology, which is used not only to compensate the time variance and nonlinearity of the channel but also to separate the needed signal from multiuser signal. In addition, fast convergence, stability and the small computational complexity of adjusting weights are required because of the high data transmission rate of UWB and short transmission time for a frame of

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data. This paper discusses the method of the equalizing technology applied in the receiver of time-hopping UWB (TH-UWB) and direct-sequence UWB (DS-UWB) system.

2 TH-UWB/DS-UWB and description of indoor multipath channel

2.1 Signal presentation

The impulse used by UWB can be expressed by the second derivative Gaussian function as: $w_{\mathrm{tr}}(t)=[1-4\pi(t/\tau_m)^2]\cdot\exp[-2\pi(t/\tau_m)^2]$ TH-UWB is written as follows:

$$\boldsymbol{S}^{(k)}_{\mathrm{tr\_TH}}(t)=\sum_{j=-\infty}^{\infty} w_{\mathrm{tr}}(t-jT_f-c_j^{(k)}T_c)(2D^{(k)}_{[j/N_s]}-1) \tag{1}$$

where T_f denotes the basic period of impulse series, pseudorandom sequence $\{c_j^{(k)}\}$ is as the additional time offset produced by time-hopping code to distinguish user address, and $0 \le c_j^{(k)} \le N_h$ .When the pseudorandom sequence is m sequence with n rank, $N_h=2^n-1$, and T_c is the minimum time-hopping interval of the pseudorandom sequence, usually $N_hT_c \le T_f$. The period of pseudorandom code is N_hT_f, $D^{(k)}_{[j/N_s]}$ is the digit, each binary digit is denoted by N_s impulses, which can be expressed as, $D^{(k)}_{[j/N_s]}=1$ with positive pulses, and $D^{(k)}_{[j/N_s]}=0$ with negative pulses, and k denotes the user's number.

DS-UWB can be expressed by

$$\boldsymbol{S}^{(k)}_{\mathrm{tr\_DS}}(t)=\sum_{i=-\infty}^{+\infty}\sum_{j=0}^{L-1} w_{\mathrm{tr}}(t-(iL+j)T_m)\,n_j^{(k)}(2D^{(k)}_{[(iL+j)/L]}-1) \tag{2}$$

Especially, assuming the length of a frame is M bits and every bit is composed of L pulses modulated with pseudorandom codes, a data frame of user k can be expressed as

$$\boldsymbol{S}^{(k)}_{\mathrm{tr\_DS}}(t)=\sum_{i=0}^{M-1}\sum_{j=0}^{L-1} w_{\mathrm{tr}}(t-(iL+j)T_m)\,n_j^{(k)}(2D^{(k)}_{[(iL+j)/L]}-1) \tag{3}$$

2.2 Channel model

This paper adopts the time-domain multipath channel model of UWB proposed by Intel [4], which is derived from the S-V model with slight modification [5]. The discrete impulse response of multipath channel is described as:

$$\boldsymbol{h}(t)=\sum_{q=0}^{Q}\sum_{p=0}^{P}\alpha_{p,q}\delta\left(t-T_q-\tau_{p,q}\right) \tag{4}$$

where $\alpha_{p,q}$ is the multipath gain coefficient, $\alpha_{p,q}=p_{p,q}\beta_{p,q}$, the term $p_{p,q}=\pm 1$ is used to account for the pulse inversion that can occur due to reflections, $\beta_{p,q}$ is the lognormal fading term, $|\beta_{p,q}|=10^{n/20}, n \propto N\left(\mu_{p,q},\sigma^2\right)$, the variance of normal distribution $E\left[\beta^2_{p,q}\right]=\Omega_0 \mathrm{e}^{-T_q/\Gamma}\mathrm{e}^{-\tau_{p,q}/\gamma}$, Ω_0 is the mean power of the first path of the first cluster, and the mean is

$$\mu_{p,q}=\frac{10\ln(\Omega_0)-10T_q/\Gamma-10\tau_{p,q}/\gamma}{\ln(10)}-\frac{\sigma^2\ln(10)}{20}$$

where Γ is cluster decay factor, γ is the ray decay factor, and T_q denotes the arrival time of the first path of the qth cluster. The distribution function of cluster arrival time is given by (Λ is cluster arrival rate) $p\left(T_q\middle|T_{q-1}\right)=\Lambda\exp\left(-\Lambda\left(T_q-T_{q-1}\right)\right)$ where $\tau_{p,q}$ is the delay of the qth path within the pth cluster relative to the first path arrival time T_q. The attribution function of path arrival time is written as (λ is path arrival rate) $p\left(\tau_{p,q}\middle|\tau_{p-1,q}\right)=\lambda\exp\left(-\lambda\left(\tau_{p,q}-\tau_{p-1,q}\right)\right)$. If the impulse response due to the channel k is $\boldsymbol{h}_k(t)$ for TH-UWB, the channel output of the user k can then be expressed as $\boldsymbol{y}^{(k)}_{\mathrm{TH}}(t)=\boldsymbol{S}^{(k)}_{\mathrm{tr-TH}}(t)\otimes\boldsymbol{h}_k(t)$.

Assuming $\boldsymbol{n}(t)$ is additive white Gaussian noise, the received signal can be written as:

$$\boldsymbol{r}_{\mathrm{TH}}(t)=\sum_{k=1}^{K}\boldsymbol{y}^{(k)}_{\mathrm{TH}}(t)+\boldsymbol{n}(t) \tag{5}$$

As for DS-UWB, the channel output of the user k can then be expressed as: $\boldsymbol{y}^{(k)}_{\mathrm{DS}}(t)=\boldsymbol{S}^{(k)}_{\mathrm{tr-DS}}(t)\otimes\boldsymbol{h}_k(t)$.

The received signal is:

$$\boldsymbol{r}_{\mathrm{DS}}(t)=\sum_{k=1}^{K}\boldsymbol{y}^{(k)}_{\mathrm{DS}}(t)+\boldsymbol{n}(t) \tag{6}$$

Figures 1 and 2 give the output waveform of a random channel impulse response and a second derivative Gaussian impulse through the channel (LOS) respectively. It can be observed from them that the delay spread of multipath is very serious.

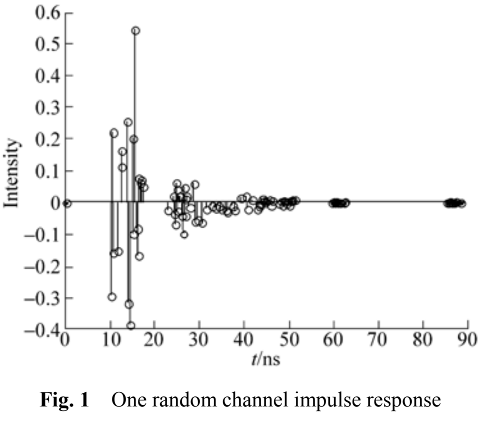

Fig. 1 One random channel impulse response

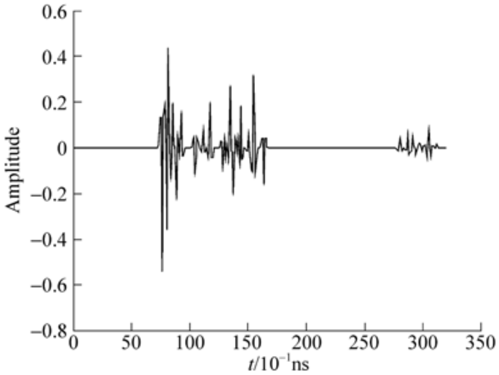

Fig. 2 Output of a second derivative Gaussian pulse through the channel

3 Time-domain equalization

When many users are active, the situation is more aggravating. Figure 3 shows the composition of 15 asynchronous active users' waveform during a T_f period. Obviously, separating these 15 users' information from the received signal is a rough task. Time domain RAKE has been discussed in many papers [6–9], but the fact is that, although the method of collecting the energy of infinite paths can get the optimum performance theoretically, it's difficult to realize in practice. The UWB multipaths that carry the main energy of the singles will be up to tens and hundreds, but the complexity acceptable RAKE receiver generally has 4-8 fingers, so more RAKE fingers will increase the complexity dramatically. Fortunately, the channel distortion can be compensated and intersymbol interference can be cancelled if the equalizer is designed reasonably in the UWB system by better searching window sizes and software radio methods.

The basic structure of the equalizing algorithm is shown in Fig. 4. First the input compositive signal of the receiver, Eq. (5) and Eq. (6), is sampled, $\boldsymbol{r}(t)\to\boldsymbol{r}(n)$, and T_s is the sampling period. In the equalizing algorithm, define:
weight vectors $\boldsymbol{w}(n)=[w_1(n)\quad w_2(n)\cdots w_N(n)]^{\mathrm{T}}$;
signal vectors $\boldsymbol{r}(n)=[r(n)\quad r(n-1)\cdots r(n-N)]^{\mathrm{T}}$.

For TH-UWB, in order to obtain a higher data transmission rate, the basic demodulated unit should be impulse. According to the statistics of channel characteristics that the delay spread of single pulse is usually within 10 times its pulse width, if the width of the single pulse is 2 ns and the sampling interval is 0.1 ns, N=200(2 ns) can be selected. For DS-UWB, similar to CDMA, since a digit consists of compact impulse arranged in terms of the pseudorandom codes, the basic demodulated unit can be data bit and the main component of delay spreads is taken as the integral multiple of code width. With the figure of channel properties above, the bit energy, after being delayed and spread, is mainly within double width of a bit. Assuming the width of signal pulse is 0.6 ns and the interval of sampling is 0.1 ns, then $N=2\times15\times0.6\div0.1=180$(18 ns) is viable.

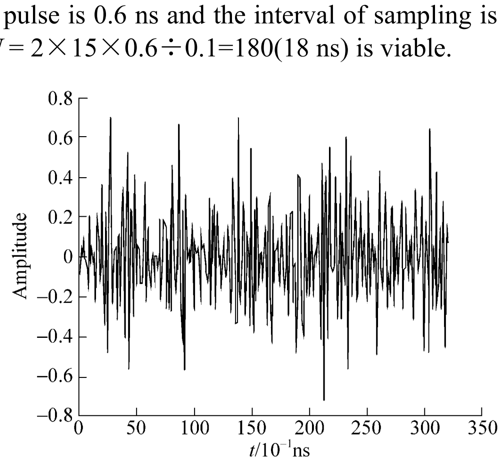

Fig. 3 Compositive waveform in T_f period with K=15 (TH-UWB)

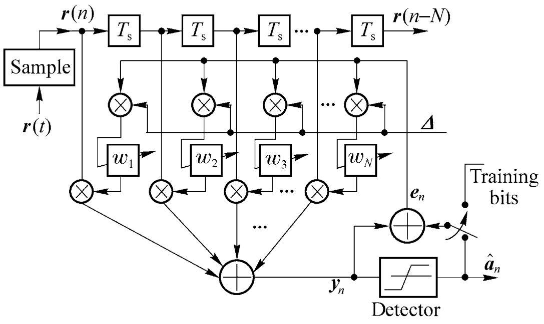

Fig. 4 Basic structure of the equalizing algorithm

The output signal is

$$\boldsymbol{y}(n)=\sum_{i=1}^{N}w_i(n)r(n-i+1)=\boldsymbol{w}^{\mathrm{T}}(n)\cdot\ \boldsymbol{r}(n)$$

The error of equalizer is $\boldsymbol{e}(n)=\hat{\boldsymbol{a}}_n-\boldsymbol{y}(n)$

The increment coefficient $\boldsymbol{\varDelta}$ in Fig. 4 plays a key role in adjusting weights, and, generally, the weights iterative formula is

$$\boldsymbol{w}(n+1)=\boldsymbol{w}(n)+\boldsymbol{\varDelta}\cdot\boldsymbol{e}(n).$$

where

$$\varDelta=\mu\boldsymbol{r}(n)\quad\text{(LMS)},$$

or

$$\varDelta=\boldsymbol{K}_N(n)=\frac{\boldsymbol{P}_N(n-1)\cdot\boldsymbol{r}^{\mathrm{T}}(n)}{\lambda+\boldsymbol{r}^{\mathrm{T}}(n)\boldsymbol{P}_N(n-1)\boldsymbol{r}(n)}\text{(RLS)},$$

and $\boldsymbol{P}_N(n)$ is the inverse of the correlation matrix of the input signal vectors

$$\boldsymbol{R}_N(n)=\sum_{i=0}^{n}\lambda^{n-i}\boldsymbol{r}(i)\cdot\boldsymbol{r}^{\mathrm{T}}(i),$$

where λ denotes forgetting factor, representing the correlation degree among the received signal in sequence.

For time domain equalization, the adaptive least mean squares and the adaptive recursive least squares algorithms are commonly used. The former is characterized by simplicity, less computational complexity and slow convergence rate whereas the latter is faster in convergence, but complex in computation and sensitive to the time variation. The property of high-speed transmission in UWB system requires fast computation and the time-varying feature of channel makes it necessary that the training sequence need not be too long and the convergence is fast. The two algorithms mentioned above are incompatible, so new requirements for the algorithm arise. Based on the characteristics of indoor dense multipath channel for UWB signal, namely users don't move too fast and the indoor environments don't change rapidly, this paper proposes a new equalizing method that uses an improved RLS algorithm for less training bits and adopts an improved LMS algorithm for the following information bits. Because the training bits are known non-information data, which can be transmitted non-real-time, its transmission rate can be lower, but its convergence quality should be high. While detecting the information bits, we should focus on the speed of convergence. Using LMS algorithm to adjust the known weights of equalizer can simplify the computation sharply, so the real-time detection can be achieved.

Modified RLS algorithm: it can be known from the correlation matrix that, the less λ is, the less important the sampling value that is far away from the current value is, and when $\lambda = 1$, all the sampling values have the same correlation degree. During the short training phase, channel can be considered unchanged, so it is available to adjust the weights by the latest sample value, namely, λ is assigned a very small value, which means increasing Δ, to speed up the convergence. As the iterative times of training increase, the weights are gradually stable. At that time, we hope that the weights are basically immune to the occasional interference from outside, and λ is considered to be a slightly larger value, which means decreasing Δ. There:

$$\lambda = \lambda_n = a\lambda_0^{b/n} \tag{7}$$

The gradually increased value and the rate of λ_n depend on the selection of a, b, λ_0. If $\lambda_0 = 1$, then $\lambda_n = a$, that is conventional RLS. If λ_n is computed in advance, complexity of algorithm is $\mathrm{O}\left(N^2\right)$ that is equivalent to the conventional RLS.

Modified LMS algorithm: Similar to modified RLS, in LMS algorithm, the constant μ is replaced by μ_n, which is given a larger value early to speed up the convergence of the algorithm, and then decreased gradually to guarantee a smaller mean square error. Here:

$$\mu_n = C^{\frac{1}{1+an^b}}\mu_0 \tag{8}$$

The selections of C, a, b decide the fading value and the fading rate of μ_n. Obviously $C \geq 1$. When $C = 1$, $\mu_n = \mu_0$, that is conventional LMS. Assuming μ_n is calculated in advance, complexity of algorithm is $\mathrm{O}(N)$ that is equivalent to the conventional LMS.

4 Results and discussions

Comparison of the modified and the conventional RLS algorithm: Figure. 5 shows the error for DS-UWB of using the improved RLS algorithm to separate all the interuser and intersymbol interference. And in the same condition, the error of using conventional RLS algorithm can be seen in Fig. 6. It is very clear that the error in Fig. 5 is less than that in Fig. 6.

Comparison of the method of using conventional RLS algorithm and that of using the RLS algorithm during the training phase and the LMS algorithm during the decision phase: Figure. 7 spots the error for TH-UWB system of using the RLS algorithm to train and using the LMS algorithm to detect all the interuser and intersymbol interference. In the same condition, the error of using the LMS algorithm is spotted in Fig. 8. It is observed that the convergence rate of using RLS during the training phase is faster, and RLS-based weights can be normally shifted to LMS algorithm during the decision phase so that the decision can be made quickly. If conventional LMS is adopted, it can be seen from Fig. 8 that the convergence rate is slower.

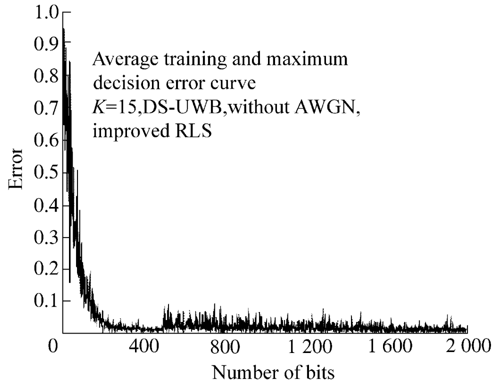

Fig. 5 Error using modified RLS to separate interuser and intersymbol interference (DS-UWB)

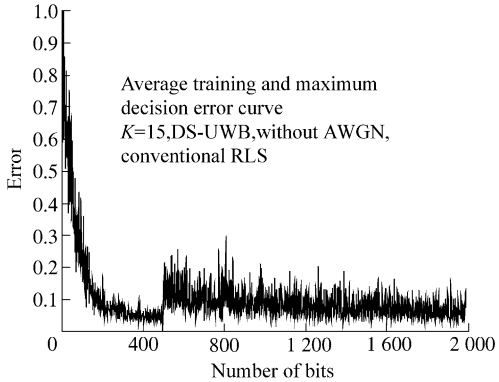

Fig. 6 Error using conventional RLS to separate interuser and intersymbol interference (DS-UWB)

The situation added with AWGN as well as multipath interference: using RLS algorithm in the training and decision phase is denoted as (RLS, RLS) which is shown in Fig. 10. Adopting modified RLS algorithm when training while adopting modified LMS when detecting , is presented as (RLS, LMS) shown in Fig. 9. Under the same condition of DS-UWB system and E_b/N_0 = 16 dB on the output of the receiver (given a standard variance of 0.14), it can be seen that error in Fig. 9 is less than that in Fig. 10.

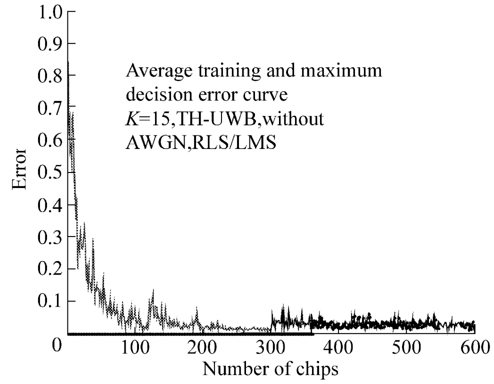

Fig. 7 Error using (RLS, LMS) to separate interuser and intersymbol interference (TH-UWB)

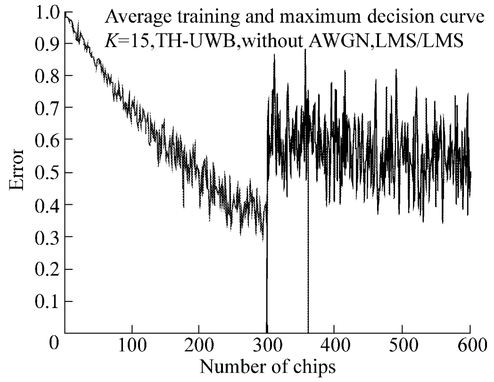

Fig. 8 Error using conventional LMS to separate interuser and intersymbol interference (TH-UWB)

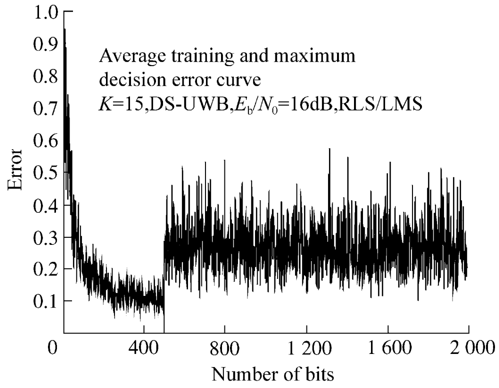

Fig. 9 Error using (RLS,LMS) with E_b/N_0=16 dB (DS-UWB)

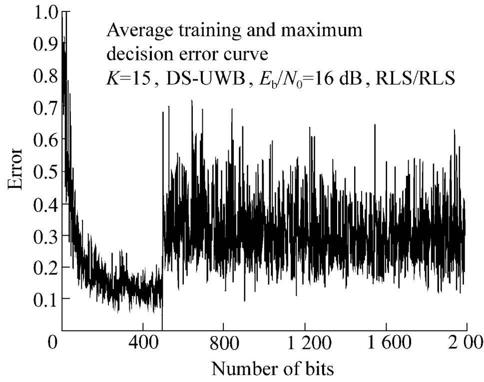

Fig. 10 Error using (RLS,RLS) with E_b/N_0=16 dB (DS-UWB)

BER of TH-UWB and DS-UWB assuming the same E_b/N_0 on the output of receiver: Figure. 11 compares the (RLS, RLS) with (RLS, LMS) by simulation. For DS-UWB, the performance of (RLS, LMS) is obviously better than that of (RLS, RLS), and also than that reported in Ref. [10]. In TH-UWB, both BER is very close so only one curve is plotted, but the computational time of (RLS, LMS) is less than that of(RLS, RLS). However, note that, using the symbol as the demodulation unit in DS-UWB is easier to implement.

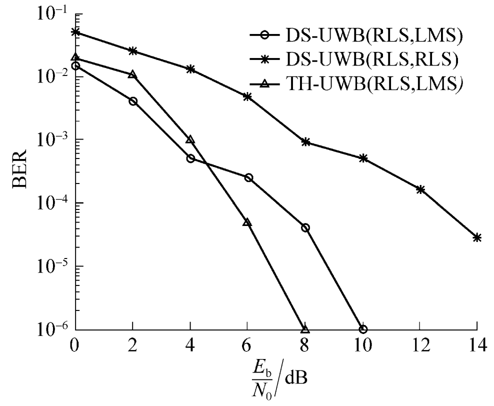

Fig. 11 BER using(RLS, RLS)and(RLS, LMS)for TH-UWB and DS-UWB

5 Conclusions

This paper analyzes the signal and channel for TH-UWB and DS-UWB separately. Based on which, an adaptive equalizer is used to compensate the distortion caused by the multipath and AWGN channel and presents a new method aimed at the characteristics of UWB, which can not only reduce the bit number needed for training and speed up the convergence process during training phase but also adjust weights quickly, decrease the computation complexity during the decision phase and lower the BER. The main strategy of this method is to use different adaptive equalization algorithms at the training and decision phase, and also properly to amend the conventional RLS and LMS in the algorithm. Because λ_n in the modified RLS and μ_n in the modified LMS can be calculated in advance, the complexity of the new scheme combining the two together is much lower compared with using RLS alone.

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