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RESEARCH ARTICLE

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The BER performance optimization of ultra wideband TH-PPM in a multi-path environment

Abstract This paper is focuses on the unbalanced bit error rate (BER) for different transmitted data symbols of ultra wideband (UWB) impulse radio time-hopping pulse-position-modulation (TH-PPM) in a deterministic multi-path environment for unreasonable parameter selection. Two solutions are presented here. The first is that the decision threshold of RAKE is dynamic for different channel environments; the other is that we can improve the traditional TH-PPM modulation, which is, encoding the transmitted data symbol with balance code. It is shown by theoretical analysis and computer simulation that these two methods can solve the unbalanced BER of traditional TH-PPM. Compared with the dynamic threshold method, the balance encoding scheme can be implemented more easily, and is more robust to the channel time variant characteristics, the channel estimation of RAKE receiver and the combination techniques.

Keywords ultra wideband radio, performance optimization, dynamic threshold, balance encoding

1 Introduction

UWB communication techniques have attracted a great interest in both academia and industry in the past few years. Following the re-definition of UWB signal given by the FCC [1], communication techniques of UWB radio developed from impulse radio (IR) to the co-existence of three techniques, IR, MB-OFDM and DS-CDMA, two of which, MB-OFDM and DS-CDMA, were included in the main proposal for IEEE 802.3a standard. IR has received significant attention during the establishment of the IEEE 802.3a standard due to its potential advantages such as simple system structure, low cost and low power. This technique plays an important part in future short distance, high rate wireless communication of especially for extending the Internet, WPAN, mobile wire-less network and wireless multimedia, which has a tremendous wide foreground for applications.

IR-UWB is a non-sine system that conveys information with pulses of very short duration, whose characteristics through multi-path propagation have great differences from the conventional radio. Thus, special attention should be paid, for example, on its penetrating characteristics. Experiments were performed in Refs. [2, 3] to measure the characteristics of UWB signal through multi-path propagation both indoor and outdoor. At present, the channel model for indoor UWB communication has been defined basically [4]; The methods to select UWB signal in indoor environment are given in Ref. [5], while the problem about capturing energy from the received signal in a multi-path environment for UWB signal was analyzed in Ref. [6].

As the most classical modulation of IR-UWB communication, TH-PPM has been researched in many papers. In Refs. [7, 8] we mainly discussed about the BER performance of signal modulated by TH-PPM, and pointed out that under the condition of deterministic multi-path channel, the BER would become imbalance between ‘0’ and ‘1’ while adopting TH-PPM receiver with zero-cross detection. Different performances of multi-path combination methods while adjudging symbols with the RAKE receiver adopting zero-cross detection were discussed in Ref. [9]. Because the IR signal consists of tremendous numbers of multi-path components, multi-finger RAKE receiver will improve the system complexity, so we propose two methods to improve the performance of TH-PPM modulation based on

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Refs. [7, 8].

2 Signal model and structure of receiver

2.1 Classical modulated signal by TH-PPM

Transmitted waveform modulated by TH-PPM [9] is

$$S_d\left(t\right)=\frac{1}{\sqrt{N_s}}\sum_{j=0}^{N_s-1} w\left(t-j\,t_f-C_j^{(k)}\,t_c-\delta\,d\right) \tag{1}$$

where superscript k represents the kth user of the system; $w(t)$ is the transmitted monocycle pulse, and the pulse duration time is w_b; t_f is the pulse repetition time, and $w_b << t_f$; $C_j^{(k)}=C_{j+mN_p}^{(k)}$ is the jth code of the kth user's PN code, where $m=0,1,2,\cdots$, N_s represents the PN code cycle period, and $0<C_j^{(k)}\le N_h$; N_h is maximum of $C_j^{(k)}$, and $N_h t_c < t_f$; t_c is the unit delay of the transmitted pulse constrained by the PN code; δ is the unit delay of the transmitted pulse constrained by the binary code (also noted as modulation index), $d\in\{0,\ 1\}$, and a binary code is transmitted every N_s monocycle pulses. The bandwidth of the monocycle pulse is $B_c\approx 1/w_b$, the duration time of every bit symbol is $T_{\text{bit}}=N_s t_f$, and the information transmitting speed is $R_{\text{b}}=1/T_{\text{bit}}$. The modulation index δ, the unit delay of the transmitted pulse t_c constrained by the PN code and the pulse duration time w_b are at the same level quantitatively. The normalized self-correlation function of $w(t)$ is:

$$R\left(\tau\right)=\frac{\int_{-\infty}^{\infty} w\left(t\right)w\left(t-\tau\right)\mathrm{d}t}{\int_{-\infty}^{\infty} w^2\left(t\right)\mathrm{d}t} \tag{2}$$

The energy of every bit is:

$$E_{\text{b}}=\int_{-\infty}^{\infty} {S_d}^2\left(t\right)\mathrm{d}t \tag{3}$$

2.2 The receiver structure

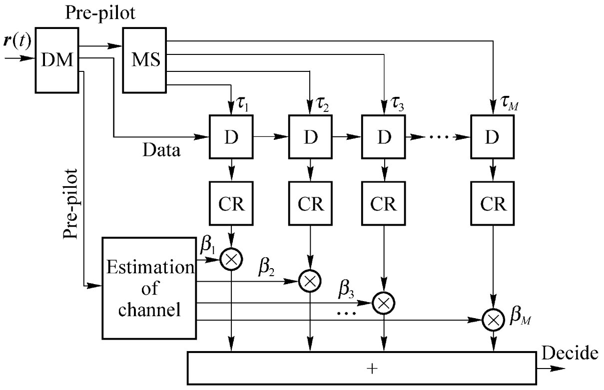
We adopt the UWB indoor channel model proposed by the IEEE 802.15.3a working group [4] as our channel model, and the impulse response of the channel is:

$$h(t)=\sum_{l=0}^{L-1}\alpha_l\delta(t-\tau_l) \tag{4}$$

where α_l represents the amplitude decline and τ_l represents the time delay of the lth multi-path component. They are all real. L is the multi-path number, and the maximal multi-path component time delay $\tau_L < t_f$. Here we assume $\left|\tau_l-\tau_k\right|\ge T_p$, $\forall l\ne k$, where T_p is the width of $w(t)$, because two paths with relative time delay less than a pulse width can not be resolved by the RAKE receiver. Thus, without consideration of pulse waveform distortion, the received signal is

$$\boldsymbol{r}(t)=\sum_{l=0}^{L-1}\alpha_l S_d(t-\tau_l)+\boldsymbol{n}(t) \tag{5}$$

where $n(t)$ is the gauss white noise with bilateral power spectrum density $N_0/2$. The RAKE receiver structure is shown in Fig. 1. Where β_m and τ_m' represent the decline and time delay of the mth finger of the receiver, respectively.



DM: demultiplexing MS: multipath search CR: correlate

Fig. 1 Structure of UWB RAKE receiver

3 The imbalance BER of TH-PPM

The conditional BER performance of the output data by the zero-cross detection is proposed in Ref. [8], when the '0' is transmitted, the decision threshold is

$$\begin{aligned}U_0 &= E_{\text{b}}\sum_{m=0,\tau_l\ne\tau_m'}^{M-1}\alpha_m\beta_m\{1-R(\delta)\}\\ &\quad -E_{\text{b}}\sum_{m=0}^{M-1}\sum_{l=0,\tau_l\ne\tau_m'}^{L-1}\alpha_l\beta_m R(\tau_l-\tau_m'-\delta)+\xi\end{aligned} \tag{6}$$

where $\xi\sim N\left(0,N_0E_{\text{b}}(1-R(\delta))\sum_{m=0}^{M-1}\beta_m^2\right)$

The BER performance of the RAKE receiver is

$$P(1/0)=Q\left(\frac{K_0}{\sqrt{N_0E_{\text{b}}\left[1-R(\delta)\right]\sum_{m=0}^{M-1}\beta_m^2}}\right) \tag{7}$$

$$\begin{aligned}K_0 &= E_{\text{b}}\sum_{m=0,\tau_l=\tau_m'}^{M-1}\alpha_m\beta_m\{1-R(\delta)\}\\ &\quad -E_{\text{b}}\sum_{m=0}^{M-1}\sum_{l=0,\tau_l\ne\tau_m'}^{L-1}\alpha_l\beta_m R(\tau_l-\tau_m'-\delta)\end{aligned} \tag{8}$$

When the '1' is transmitted, the decision threshold is

$$U_1 = E_b \sum_{m=0,\tau_l=\tau'_m}^{M-1} \alpha_m\beta_m\{R(\delta)-1\} + E_b \sum_{m=0}^{M-1}\sum_{l=0,\tau_l\neq\tau'_m}^{L-1} \alpha_l\beta_m R(\tau_l-\tau'_m+\delta)+\xi' \tag{9}$$

where $\xi \sim N\left(0, N_0E_b(1-R(\delta))\sum_{m=0}^{M-1}\beta_m^2\right)$

The BER performance of the RAKE receiver is

$$P(0/1) = Q\left(\frac{-K_1}{\sqrt{N_0E_b\left[1-R(\delta)\right]\sum_{m=0}^{M-1}\beta_m^2}}\right) \tag{10}$$

$$K_1 = E_b \sum_{m=0,\tau_l=\tau'_m}^{M-1} \alpha_m\beta_m\{R(\delta)-1\} + E_b \sum_{m=0}^{M-1}\sum_{l=0,\tau_l\neq\tau'_m}^{L-1} \alpha_l\beta_m R(\tau_l-\tau'_m+\delta) \tag{11}$$

If the system is transmitting '0' and '1' equiprobably, i.e., both equals 1/2, then the BER of the system is

$$P_e = \frac{1}{2}Q\left(\frac{K_0}{\sqrt{N_0E_b\left[1-R(\delta)\right]\sum_{m=0}^{M-1}\beta_m^2}}\right) + \frac{1}{2}Q\left(\frac{-K_1}{\sqrt{N_0E_b\left[1-R(\delta)\right]\sum_{m=0}^{M-1}\beta_m^2}}\right) \tag{12}$$

As seen in Eqs. (8) and (11), different system parameter selection will cause the inequality of K_0 and K_1. Therefore, the TH-PPM UWB communication system will introduce a BER imbalance between transmitting '0' and '1', which was depicted in detail in Ref. [9] and the conclusion that balanced BER performance can be reached by adopting MRC combination in A-RAKE receiver with decision threshold as 0, while for any other combination method, BER performance is imbalance usually with decision threshold as 0.

As communication theory indicates, the BER performance of a system can't reach the optimal state, if BER for equiprobable '0' and '1' are unequal. That is to say the receiver performance of the system would reach the optimal state under the minimum BER rule.

4 Methods to eliminate imbalance of BER in PPM system

In order to make the BER performances of the TH-PPM RAKE receiver reach the optimal state, we have to resolve the problem about the imbalance of BER for different data symbols. Dynamic threshold and symmetric encoding of transmitted data symbol will be discussed in this section.

4.1 Dynamic threshold

One intuitive method to resolve the imbalance problem about BER in PPM systems is to reset the decision threshold of the RAKE receiver. In the preceding analysis of system performances, the RAKE receiver was designed with '0' in its threshold, however, as shown in Fig. 2, the mean values of decision variables U_0 and U_1 derived from transmitted symbols '0' and '1' respectively are asymmetric, according to theories of signal detection, the optimal threshold A should be set as $A = K_0 + K_1/2$.

The following formula calculates the optimal threshold:

$$A = \frac{1}{2}E_b\sum_{m=0}^{M-1}\sum_{l=0}^{L-1}\alpha_l\beta_m\left\{R(\tau_l-\tau'_m+\delta)-R(\tau_l-\tau'_m-\delta)\right\} \tag{13}$$

When the threshold equals the optimal value, BER for equiprobable '0' and '1' are equal as:

$$P(1/0) = P(0/1) = Q\left(\frac{K_0-K_1}{2\sqrt{N_0E_b\left[1-R(\delta)\right]\sum_{m=0}^{M-1}\beta_m^2}}\right) \tag{14}$$

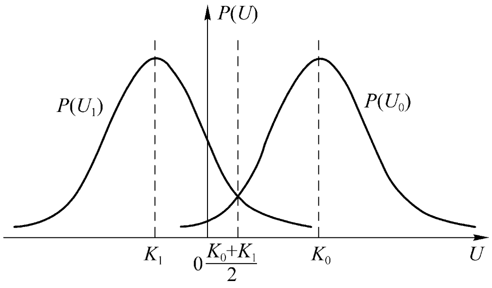


Fig. 2 PDF of decision variables of RAKE receiver

For different combination methods in the RAKE receiver, the formula to calculate the optimal threshold value can be simplified to some extent.

4.2 Balance encoding modulation

Although dynamic threshold is intuitive and easy to understand, different channel environments lead to different thresholds, and it depends on the accuracy of estimation of channel, which is difficult to implement. In this sub-section, we encode transmitted data symbols with balance code to resolve the imbalance problem about BER in PPM systems.

In conventional TH-PPM modulation, N_s pulses are used to convey one data symbol. When '1' is transmitted, the position of N_s pulses is delayed by d relative to that when '0' is transmitted; the waveform is shown in Eq. (1). In order to balance the BER, we encode the transmitted data to make the transmitted waveform symmetric in the TH-PPM system. To encode the data, we introduce in two pseudorandom binary sequences of N_s symbols, $c_i = \{c_{i,j}\}_{j=0}^{N_s-1}$, i=0,1, $c_{i,j} \in \{0,1\}$, which satisfy the following two requirements:

1) The number of ‘0’ must equal that of ‘1’,which requires the number of N_s to be even.

2) c_0 and c_1 are complement code for each other, that is, $c_{1,j} = 1 - c_{0,j}$, $j = 0,1,\cdots,N_s - 1$.

Map the transmitted binary symbol to c_0 and c_1, that is, when ‘0’ is transmitted, c_0 is used to control the relative position of the pulse, while when ‘1’ is transmitted, c_1 is used instead. And transmitted waveform is shown as follow:

$$S_i(t) = \frac{1}{\sqrt{N_s}} \sum_{j=0}^{N_s-1} w\left(t - j t_f - C_j^{(k)} t_c - c_{i,j}\delta\right) \tag{15}$$

Local correlated signal is:

$$v_{\text{bit}}(t) = w_{0,\text{bit}}(t) - w_{1,\text{bit}}(t) \tag{16}$$

where, $w_{i,\text{bit}}(t) = \frac{1}{\sqrt{N_s}} \sum_{j=0}^{N_s-1} w\left(t - j t_f - C_j^{(k)} t_c - c_{i,j}\delta\right), i = 0,1$.

Under the assumption that transmitting data symbol is ‘0’, the output of the RAKE receiver is:

$$U_0 = K_0 + \xi \tag{17}$$

$$\begin{aligned} K_0 = {} & E_{\text{b}} \sum_{m=0,\tau_l \neq \tau'_m}^{M-1} \alpha_m \beta_m \{1 - R(\delta)\} \\ & - \frac{1}{N_s} E_b \sum_{m=0}^{M-1} \sum_{l=0,\tau_l \neq \tau'_m}^{L-1} \sum_{j=0}^{N_s-1} \alpha_l \beta_m \\ & \times R(\tau_l - \tau'_m + (c_{0,j} - c_{1,j})\delta) \end{aligned} \tag{18}$$

ξ is zero-mean Gaussian random variable with variance $N_0 E_{\text{bit}} [1 - R(\delta)] \sum_{m=0}^{M-1} \beta_m^2$.

Because $c_{1,j} = 1 - c_{0,j}$, ($j = 0,1,\cdots,N_s - 1$), and the number of ‘0’ in the sequence equals that of ‘1’ here are $N_s / 2$ ‘+1’ and ‘−1’ in $\{c_{0,j} - c_{1,j}\}$, then,

$$\begin{aligned} K_0 = {} & E_{\text{b}} \sum_{m=0,\tau_l \neq \tau'_m}^{M-1} \alpha_m \beta_m \{1 - R(\delta)\} - \frac{1}{2} E_{\text{b}} \sum_{m=0}^{M-1} \sum_{l=0,\tau_l \neq \tau'_m}^{L-1} \alpha_l \beta_m \\ & \times \left[R(\tau_l - \tau'_m - \delta) + R(\tau_l - \tau'_m + \delta) \right] \end{aligned} \tag{19}$$

For the same reason，when ‘1’ is transmitted, the output of the RAKE receiver is:

$$U_1 = K_1 + \xi' \tag{20}$$

$$\begin{aligned} K_1 = {} & E_{\text{b}} \sum_{m=0,\tau_l \neq \tau'_m}^{M-1} \alpha_m \beta_m \left[R(\delta) - 1 \right] + \frac{1}{2} E_{\text{b}} \sum_{m=0}^{M-1} \sum_{l=0,\tau_l \neq \tau'_m}^{L-1} \alpha_l \beta_m \\ & \times \left[R(\tau_l - \tau'_m - \delta) + R(\tau_l - \tau'_m + \delta) \right] \end{aligned} \tag{21}$$

where, ξ' is a zero-mean Gaussian random variable with variance $N_0 E_{\text{b}} [1 - R(\delta)] \sum_{m=0}^{M-1} \beta_m^2$. And the optimal decision threshold is:

$$A = \frac{1}{2}\left(K_0 + K_1\right) = 0 \tag{22}$$

That is, when adopting the balance code proposed in this paper to encode the transmitted data symbol, even when the decision threshold equals 0, the BER of different data symbol can still reach balance, which makes the performance optimal.

From Eqs. (19), (21)–(22), we can come to the conclusion that no matter what the channel environment is, when adopting the balance encoding modulation to the transmitted data symbol in TH-PPM systems, it can always reach balance with decision threshold as 0. The selected balance code is independent of the channel environment, that is to say, the selection of c_0 and c_1 does not need the channel status information, neither the multipath channel impact on the ‘0’ and ‘1’ sequences.

Let $K = K_0$, then the BER performance of the RAKE receiver is

$$P_{\text{e}} = Q\left(\frac{K}{\sqrt{N_0 E_{\text{b}} [1 - R(\delta)] \sum_{m=0}^{M-1} \beta_m^2}} \right) \tag{23}$$

Therefore, the RAKE receiver is the optimal receiver of the TH-PPM system under minimum BER rule when ‘0’ and ‘1’ appears equiprobably. The BER balance performance of zero-cross detection RAKE receiver after balance coding will not change along with channel conditions; neither will be affected by the veracity of channel estimation and the combination type of RAKE receiver. The receiver designation is far simpler than the system using dynamic judgment threshold.

5 Simulation results

5.1 Conditions of simulation

The simulation of UWB RAKE receiver performance is implemented by MATLAB communication software under Windows OS.

In the simulation, the UWB system uses TH-PPM modulation, $N_s = 10$ and symbol rate is 4 Ms/s. The pulse waveform is the revised second derivation Schmitt pulse implemented by common IR system, i.e.,

$$w(t) = \frac{1}{(\sigma w_b)^2} \left[1 - 4\pi \left(t - \frac{w_b}{2} \right)^2 \right] \mathrm{e}^{\frac{2\pi}{(\sigma w_b)^2}\left(t - \frac{w_b}{2}\right)^2} \tag{24}$$

where $w_b = 0.2 \times 10^{-9}\,\text{s}$ is the pulse width, $\sigma = 0.447\,2$ is a constant value used to control the pulse width. The waveform of and its auto correlation function is shown in Fig. 3.

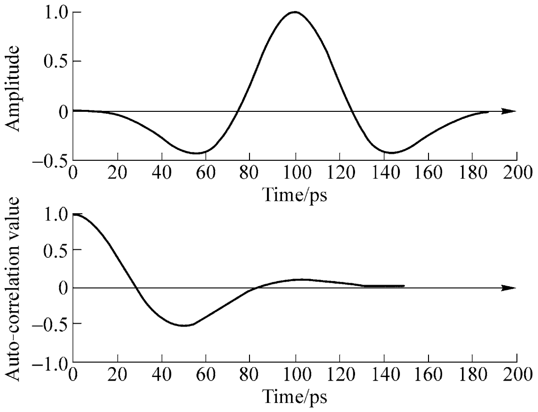


Fig. 3 The simulation pulse waveform and its auto-correlation function

5.2 Results of simulation

We adopt certain channel realization of CM2 in the indoor UWB multi-path channel model described in Ref. [3] as our simulation channel. The system does not adopt any correction code, assuming perfect synchronization at receiver front end and unbiased estimation of both multi-path amplitude and arrival time. The combination method of the RAKE receiver is MRC.

The BER performance comparison between fixed zero-cross detection and dynamic threshold detection is shown in Fig. 4. As seen from the figure, the BER performance of the system when transmitting ‘0’ and ‘1’ using dynamic threshold detection trends balance. Figure 5 describes the BER performance comparison between fixed zero-cross detection and balance encoding. As seen from the figure, the BER performance of the system when transmitting ‘0’ and ‘1’ using balance encoding trends balance.

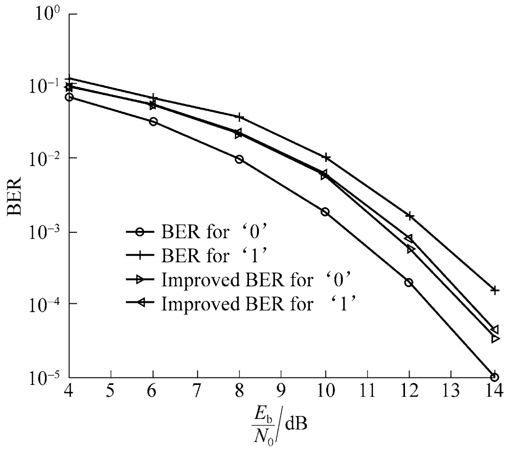


Fig. 4 The BER performance comparison before and after dynamic threshold detection

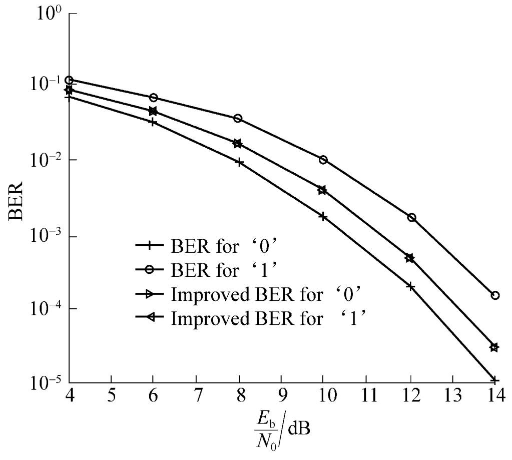


Fig. 5 The BER performance comparison before and after balance encoding

Comparing those two simulation results, we can see that the BER unbalance is completely eliminated after balance encoding. However, the BER of ‘0’ and ‘1’ using dynamic threshold have tiny difference under certain SNRs, the main reason of which is that in the simulation we use the RAKE receiver with limited number of fingers instead of full-finger RAKE receiver (the full-finger RAKE receiver is impractical in actual applications). This also indicates the limitation of dynamic threshold detection, i.e., the dynamic threshold detection is affected by the number of fingers and the combination method of the RAKE receiver and the accuracy of channel estimation.

6 Conclusions

The unbalanced BER for transmitted ‘0’ and ‘1’ of the conventional UWB TH-PPM system is discussed herein. The reason of this is that the TH-PPM system uses the relative position of pulses to convey information. However, in the UWB channel, the multi-path is so dense that the signal is interfered by nearby multi-path components when being demodulated using the RAKE receiver. This interference usually varies when the system is transmitting ’0’ or ‘1’. Two solutions are proposed aimed at this phenomenon. One is the dynamic threshold detection, and the other is balanced encoding. These two methods are proved effective through theoretic discussion and simulation. The balance encoding method improves the modulation type, and the BER balance does not depend on the accuracy of channel estimation and combination type of the RAKE receiver, while these factors have certain influence on the RAKE receiver with dynamic threshold. Appropriate choice can be made to meet the practical requirements.

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References

1. First Report and Order in the Matter of Revision of Part 15 of the Com-mission's Rules Regarding Ultra-Wideband Transmission Systems, FCC, released, ET Docket 98–153, FCC 02–48, 2002.
2. Win M. Z., Scholtz R. A., Ultra-wide bandwidth signal propagation for indoor wireless communications. In Proc. IEEE ICC, Montreal, 1997: 56–60
3. Win M. Z., Ramirez-Mireles F. Scholtz R. A. et al., Ultra—wide bandwidth signal propagation for outdoor wireless communications. In Proc. IEEE VTC, Phoenix Arizona, 1997: 251–255
4. Molisch A. F., Foerster J. R., Pender Grass M., Channel models for ultra wideband personal area networks, IEEE Wireless Communications, 2003, 10(6): 14–21
5. Choi J. D., Stark W. E., Performance of ultra-wideband communications with suboptimal receivers in multipath channels, IEEE Journal on Selected Areas in Communications, 2002, 20(12): 1754–1766
6. Win M. Z., Scholtz R. A., On the energy capture of ultrawide bandwidth signals in dense multipath environments, IEEE Communication Letters, 1998, 2(9): 245–247
7. Yue G., Ge L., Li S., Performance of UWB time-hopping spread-spectrum impulse radio in multipath environments, In Proc. IEEE VTC, 2003: 1644–1648
8. Yue G., Chen J., Luo T., et al., BER performance analysis of UWB impulse radio RAKE receiver in multipath channel, Dynamics of Continuous, Discrete and Impulsive Systems(Series B), 2005, 12(3): 397–413
9. Scholtz R. A., Multiple access with time-hopping impulse modulation, In Proc. IEEE MILCOM, 1993: 447–450
10. Xiang Jing-cheng, Wang Yi-qing, Mao Zi-can, Signal detection and estimation, Beijing: Publishing House of Electronics Industry, 1994, 38–47 (in Chinese)