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A new time-hopping/direct-sequence biorthogonal PPM UWB communication system

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Abstract

In order to increase the capacity and diminish the multiple access interference (MAI) of an ultra-wideband (UWB) system, we propose a new time-hopping/direct-sequence (TH/DS) scheme using N -ary biorthogonal pulse position modulation (BPPM). In contrast with the conventional TH/DS systems employing fixed partition of the TH slots (Shen and Ueng, Proceedings of the IEEE VTC-Spring, 2010), the proposed TH/DS system can put the start location of the TH slot in any one of Q available pulse positions within the frame. In the proposed TH/DS system, the modulation level of BPPM can be increased and the multiple access capability can be improved without degrading the system performance. Compared with the existing TH-UWB system that employs the whole frame to carry out TH process (Shen et al. IEEE Trans. Veh. Technol. **59**(2), 742-753, 2010), the proposed system has the merits of smooth power spectral density and low receiver complexity. In this article, we also derive the probability distribution of MAI for each correlator's output of the proposed TH/DS system based on the analytic characteristic function technique. In order to verify the correctness of the performance analyses and to demonstrate the effectiveness of the proposed TH/DS system, some simulation results are given in both the additive white Gaussian noise channel and the realistic UWB fading channels. From the simulation results, we find that the proposed TH/DS system outperforms the conventional TH/DS scheme.

Keywords: characteristic function (CF), time-hopping (TH), ultra-wideband (UWB), multiple access interference (MAI)

1 Introduction

Owing to the demand of short-range high-speed wireless data communication, the impulse radio ultra-wideband (IR-UWB) transmission which transmits extremely short impulses (referred to as monocycles) becomes an attractive technology recently [1]. The high ratio of transmitted signal bandwidth to data signal bandwidth makes UWB technique useful for multiple access applications. The modulation schemes that consist of pulse amplitude modulation (PAM), pulse position modulation (PPM), and pulse position amplitude modulation (PPAM) are widely adopted in IR-UWB systems. PPM and PAM modulations use the precise position and amplitude of impulses, respectively, to convey data message, while PPAM exploits both the position and amplitude of mono-cycle to carry information. $N(= 2M)$ -ary biorthogonal PPM (BPPM) which combines binary PAM and

M -ary PPM is a special case of PPAM. Under the same throughput, N -ary BPPM can provide better performance and less complexity than those of M -ary PPM [2,3].

The time-hopping (TH) and direct sequence (DS) multiple access schemes are applied in IR-UWB systems. In the conventional TH UWB system, each symbol duration is divided into N_s frames, and each frame interval is divided into N_c time slots (chips). A data symbol is modulated based on the adopted modulation scheme to transmit one pulse in each frame duration. Afterward, the position of the time slot in each frame on which the modulated pulse is located is selected and hopped from frame to frame according to the pseudorandom TH code. However, the use of PPM and/or PAM signaling in conventional TH system has one disadvantage that the line spectral occurs in the spectrum of the transmitted signals. This is because the same polarity (unipolar) of monocycles are transmitted in a given symbol period. To alleviate the effect of this problem, the conventional TH systems exploiting the randomized polarity

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(bipolar) of the transmitted pulses, also called the hybrid TH/DS system, are studied in [3,4]. The selections of the user-specific TH codes, corresponding to the utilized time slots, and the polarity (DS) codes are well designed

to mitigate the multiple access interference (MAI) and improve the system capability.

In Figure 1, all of the users transmit their signals in the same symbol period. The matrix representations of

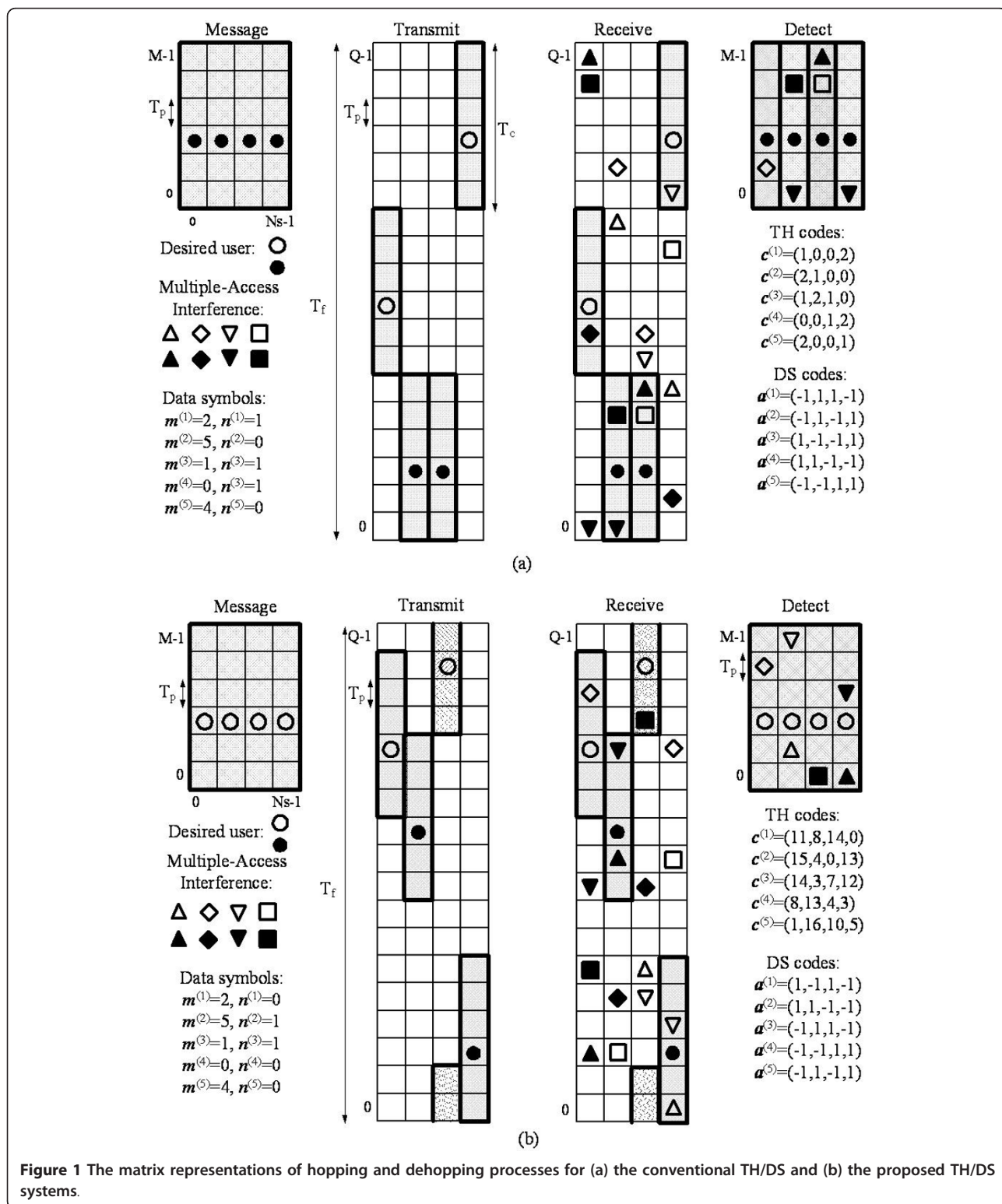


Figure 1 The matrix representations of hopping and dehopping processes for (a) the conventional TH/DS and (b) the proposed TH/DS systems.

the TH and dehopping processes are carried out in a deterministic manner. A drawback of the conventional TH system is that the greater the modulation level of the N -ary BPPM or the number of frame (\widehat{N}_s) is, the fewer the number of the provided TH slots (\widehat{N}_c) becomes. In this article, a flexible TH scheme that employs the whole frame duration to carry out TH is proposed. In the proposed system, each symbol duration is divided into N_s frames, but each frame interval is partitioned into Q pulse slots. Specifically, each user is assigned a random TH code such that the first pulse position of a TH slot can be located to any one of Q available pulse slots within one frame. Therefore, the MAI in the proposed system is hardly produced from the same interfering user's signal because of the randomness location of the transmitted pulses within each used TH slot. However, in the conventional TH scheme, the MAI that leads to an erroneous symbol detection is often produced from the same interfering user's signal. When the number of frame is increased to be the largest, then the number of TH slot becomes $\widehat{N}_c = 1$, i.e., there is no TH capability to be provided in the conventional system. In the same scenario, the TH capability still exists in the proposed system. Therefore, the impact of MAI on the system performance in the conventional scheme is more severe than that in the proposed scheme. Hence, irrespective of the modulation level of BPPM, the performances of the proposed scheme is always better than that of the conventional scheme.

In asynchronous MA environment, the collisions of the received pulses from different users are inevitable because of the randomness of time misalignment among the received signals of all the users. Compared with binary modulation, it is well known that N -ary biorthogonal modulations are able to provide higher throughput and better BER performance, as the modulation level is increased [5]. The benefit of the proposed TH scheme is able to increase the modulation level of N -ary BPPM signaling without decreasing the number of TH slots. Consequently, the proposed TH method employing larger modulation level can carry more information bits in a symbol duration and then improve the system throughput. At the transmitter of the proposed TH/DS system, the TH-coded symbol sequence of each user is first generated according to the specific TH code (hopping pattern) and becomes as the input of N -ary BPPM modulator which also applies specific DS code to randomize the polarity of the modulated pulses. The proposed TH technique has been widely employed in the frequency-hopping (FH) system which combines a larger modulation level of M -ary FSK modulation and provides better performance [6,7].

For the conventional TH-UWB systems with binary PAM and/or PPM modulations in asynchronous MA scenarios, the performance analyses have been extensively investigated in [4,8-15]. For the conventional TH-UWB systems with M -ary orthogonal PPM and N -ary biorthogonal PPM modulations, some relative studies have been reported in [16-20] and [2,21]. The Gaussian distribution assumption can be adopted to model the MAI statistics to derive some simple theoretical analyses for the binary PPM, M -ary orthogonal PPM and N -ary biorthogonal PPM signaling [2,8-10,16]. However, if we consider the medium and high signal-to-noise ratio (SNR) conditions, the Gaussian approximation (GA) fails to model the statistics of MAI precisely [4,11-13,18,20]. The exact expression of the cumulative distribution function (CDF) of the MAI is inconsistent with that obtained by using the GA. Hence, using GA leads to inaccurate error probability analysis and also leads to optimistically overestimate the system performance. By deriving the characteristic functions (CF) of the MAI, the accurate performance analyses of binary PPM/TH, M -ary orthogonal PPM/TH and N -ary BPPM/TH/DS UWB systems were proposed in [3,12-14,20]. In this article, the analytic CF expression of the MAI is derived and the performance analyses of the proposed TH/DS-UWB system is then obtained.

The rest of this article is organized as follows. The conventional and the proposed TH/DS systems with N -ary BPPM are described in Section 2. In Section 3, the analytic expression of the probability distributions of MAI and the average symbol error rate (SER) of the proposed TH/DS system is derived. Some numerical examples and discussions for the proposed system are presented in Section 4. Finally, we give some conclusions in Section 5.

2 System model

In this section, the performance of the proposed TH/DS-UWB system will be compared with that of the conventional DS-UWB system and the conventional TH/DS UWB system. The conventional DS-UWB signal can be expressed as follows [13,14]:

$$s_{\text{DS}}^{(k)}(t) = \sqrt{\frac{E_b}{N_r}} \sum_{j=-\infty}^{\infty} \sum_{n=0}^{N_r-1} d_j^{(k)} c_n^{(k)} p(t - jT_f - nT_c) \quad (1)$$

where $c_n^{(k)} \in \{1, -1\}$ denotes the n th chip of the k th user's spreading sequence; E_b is the average bit energy; $d_j^{(k)} \in \{1, -1\}$ is the j th message bit of the k th user; and N_r denotes the number of chips in a bit duration. For the conventional TH/DS system using N -ary BPPM, we divide one symbol duration T_s into N_s equally spaced

frames with duration T_f , and each frame interval T_f is divided into N_c equally spaced time slots (chips) with duration T_c . The N -ary BPPM-modulated signal is transmitted and located on one of the available N_c chips according to the assigned TH code for each user. The N -ary BPPM-modulated signal is the antipodal version of the $M(= N/2)$ -ary PPM signal. For the i th symbol period of the k th user, the N -ary BPPM signal of the conventional TH/DS system can be modeled as

$$s^{(k)}(t) = \sum_i (-1)^{n_i^{(k)}} b^{(k)}(t - iT_s - m_i^{(k)}\delta) \quad (2)$$

where t is the time index, $m_i^{(k)} \in \{0, 1, 2, \dots, M-1\}$ and $n_i^{(k)} \in \{0, 1\}$ denote $\nu-1$ bits and one bit of the i th message symbol, respectively. Overall, $u_i^{(k)} = (m_i^{(k)}, n_i^{(k)})$ represents a ν -bit message symbol and maintains the same in the i th symbol duration. In addition, the signal waveform of the k th user can be written as

$$b^{(k)}(t) = \sqrt{\frac{E_s}{N_s}} \sum_{j=iN_s}^{(i+1)N_s-1} a_j^{(k)} p(t - jT_f - c_j^{(k)}T_c) \quad (3)$$

where E_s is the average symbol energy which is assumed to be the same for all the users' signals, N_s is the number of transmitted pulses required to represent one symbol of message, $c_j^{(k)} \in \{0, 1, 2, \dots, N_c-1\}$ is the j th element of the k th user's TH code, and $a_j^{(k)} \in \{-1, 1\}$ is the j th element of the k th user's random polarity code (or random DS spreading code). To reduce the effect of MAI, it can be well designed to assign the specific random TH code $\mathbf{c}^{(k)} = (c_0^{(k)}, c_1^{(k)}, \dots, c_{N_s-1}^{(k)})$ and random polarity (DS) code $\mathbf{a}^{(k)} = (a_0^{(k)}, a_1^{(k)}, \dots, a_{N_s-1}^{(k)})$ to the k th user. δ denotes the time shift between two adjacent positions for the BPPM signals and is selected to be the pulse width T_p due to the assumption of orthogonal BPPM signaling. Therefore, the chip duration on which a M -ary PPM signal is located is equal to $T_c = MT_p$. It is worthy to note that each frame duration is partitioned into N_c non-overlapped time (chip) slots, the pulse positions of the N_s transmitted BPPM signals in the N_s selected chip slots are the same and are illustrated in Figure 1a.

For UWB systems, several pulse waveforms have been proposed. The normalized second-order Gaussian monocycle, $p(t) = [1 - 4\pi(t/\tau_p)^2] \exp[-2\pi(t/\tau_p)^2]$, which has been widely applied in many studies of the literature is adopted in this article as data bearing waveform. The

duration of the normalized second-order Gaussian monocycle is T_p . In addition, the normalized autocorrelation function of $p(t)$ is defined as $\int_{-\infty}^{\infty} p(t)p(t-\tau)dt = [1 - 4\pi(\tau/\tau_p)^2 + 4\pi^2/3 \cdot (\tau/\tau_p)^4] \exp[-\pi(\tau/\tau_p)^2]$ [8,12].

The block diagram of the proposed TH/DS-UWB system with N -ary BPPM signaling is depicted in Figure 2. The data bit stream is with rate R_b bits/s and is then mapped into an N -ary BPPM symbol sequence with rate R_s symbols/s, where $R_s = 1/T_s = 1/\nu T_b$, and $\nu = \log_2 N$ is the number of bits per symbol. In the proposed system, each frame interval is partitioned into Q equally spaced pulse slots with duration T_p . The user's signal can be located in the whole frame duration, i.e., Q overlapped and cyclic TH slots shown in Figure 1b, to carry out TH process. In the proposed TH/DS system, the number of utilized pulse positions for N -ary BPPM signaling, i.e., $M = N/2$, can be chosen as $M \leq Q$. For the conventional TH/DS system, the matrix representations of TH and dehopping processes are illustrated in Figure 1a. In the proposed TH/DS system (Figure 1b), the k th user is assigned a specific TH address code $\mathbf{c}^{(k)} = (c_0^{(k)}, c_1^{(k)}, \dots, c_{N_s-1}^{(k)})$ and a random polarity (DS) code $\mathbf{a}^{(k)} = (a_0^{(k)}, a_1^{(k)}, \dots, a_{N_s-1}^{(k)})$, where $c_j^{(k)} \in G = \{0, 1, 2, \dots, Q-1\}$. $c_j^{(k)}$ denotes the j th code element of the TH code to locate the first pulse position of the N -ary BPPM signaling in the j th frame duration. $a_j^{(k)} \in \{-1, 1\}$ is the j th element of the DS code. The signal of the proposed TH/DS system with N -ary BPPM signal is given by

$$s_{new}^{(k)}(t, i) = \sqrt{\frac{E_s}{N_s}} \sum_{i=-\infty}^{\infty} \sum_{j=iN_s}^{(i+1)N_s-1} (-1)^{n_i^{(k)}} a_j^{(k)} p(t - jT_f - b_j^{(k)}\delta) \quad (4)$$

where N_s is the number of frames. N_s pulses are transmitted to represent a ν -bit message symbol $u_i^{(k)} = (m_i^{(k)}, n_i^{(k)})$. E_s denotes the energy of a monocycle. $b_j^{(k)}$ can be obtained as $b_j^{(k)} = c_j^{(k)} \oplus m_i^{(k)}$, $m_i^{(k)} \in \{0, 1, 2, \dots, M-1\}$ denotes a $(\nu-1)$ -bit data symbol and \oplus denotes the modulo- Q addition. Specifically, the values of the two symbols, $b_j^{(k)}$ and $a_j^{(k)}$, determine, respectively, the position and amplitude of a N -ary BPPM signal transmitted in the j th frame duration. The complexities of the conventional and the proposed TH/DS schemes are almost the same if small N (8, 16, or 32) is adopted. However, the proposed TH/DS system can adopt large N (64, 128, or 256) that is infeasible for the conventional TH/DS system. In other words, the proposed TH/DS scheme is more flexible than the conventional TH/DS scheme. In asynchronous multipath additive white Gaussian noise (AWGN) channel, the

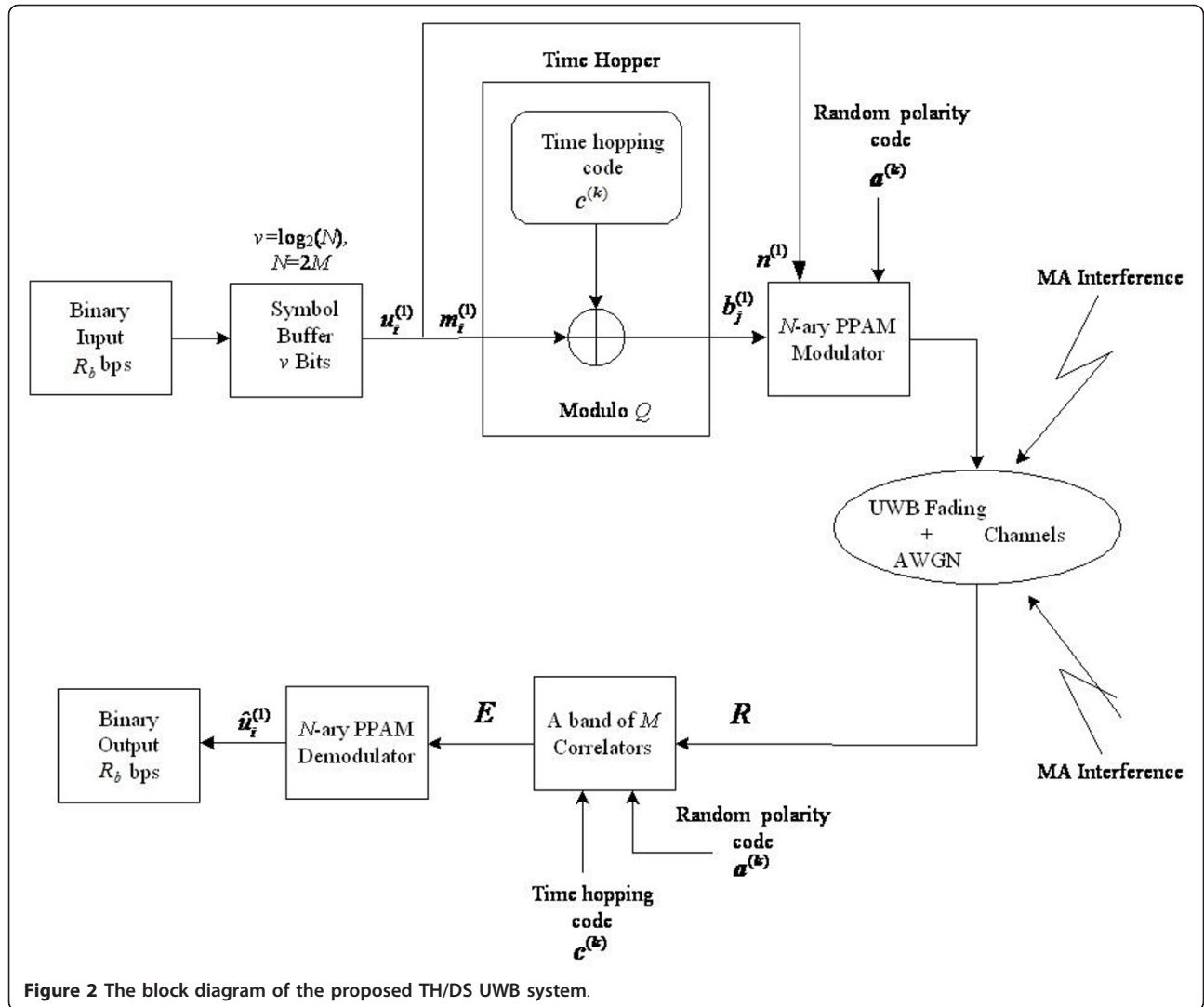


Figure 2 The block diagram of the proposed TH/DS UWB system.

received signal is $r(t) = \sum_{k=1}^K A_k s_r^{(k)}(t - \tau_k) + n(t)$, where K is the number of users, A_k is the channel attenuation of the k th signal $s_r^{(k)}(t)$, τ_k is the propagation delay of the k th signal, and $n(t)$ is the AWGN with zero mean and two-sided power spectral density; $N_0/2$. Let $s_r^{(1)}(t)$ be the desired signal, and $u_i^{(1)} = (m_i^{(1)}, n_i^{(1)})$ is the corresponding desired data symbol in the i th symbol period. Assume that the desired signal is perfectly synchronized at the receiver. ($\tau_1 = 0$) and $\{\tau_k\}_{k=2}^K$ are assumed to be uniformly distributed random variables over one symbol duration [4,13]. $s_r^{(k)}(t) = s^{(k)}(t) \otimes h^{(k)}(t)$, where \otimes denotes convolution operation, $s^{(k)}(t)$ is the k th user's signal of the DS, the conventional TH/DS, or the proposed TH/DS scheme described as (1), (2), or (4). $h^{(k)}(t)$

is the UWB channel model [22]. We also fix the required bandwidth $W = 1/T_p$ and the transmission bit rate $R_b = 1/T_b$ to have fair comparison of the performances among the systems. For the DS-UWB system, the bit interval is $T_b = T_f = N_r \times T_p$, and the processing gain is $T_b/T_p = N_r$ [13]. In cases of the conventional TH/DS system [3], we obtain

$$\frac{T_b}{T_p} = \frac{\widehat{N}_s \times \widehat{N}_c \times \widehat{M}}{\log_2 \widehat{N}} \quad (5)$$

in which the notations with $\widehat{(\cdot)}$ denote the system parameters used in the conventional TH/DS system. For the proposed TH/DS system, the symbol duration is

$$\begin{aligned} T_s &= N_s \times T_f = N_s \times Q \times T_p \\ &= (\log_2 N) \times T_b \end{aligned}$$

and so the ratio of T_b and T_p is

$$\frac{T_b}{T_p} = \frac{N_s \times Q}{\log_2 N} \quad (6)$$

3 Performance analysis

For the conventional TH/DS system using N -ary BPPM in AWGN channel, to detect the i th data symbol of the desired user $\hat{u}_i^{(1)}$, the received signal is correlated with $\hat{M}(= \hat{N}/2)$ orthogonal template waveforms to obtain \hat{M} decision statistics $\{r_m\}_{m=0}^{\hat{M}-1}$ as follows [3]:

$$r_m = \sum_{j=i\hat{N}_s}^{(i+1)\hat{N}_s-1} \int_{jT_f}^{(j+1)T_f} r(t)h_m(t-jT_f)dt = \begin{cases} S_{\text{conv}} + I_{\text{conv}} + n_{\text{conv}}, & m = m_i^{(1)} \\ I_{\text{conv}} + n_{\text{conv}}, & m \neq m_i^{(1)} \end{cases} \quad (7)$$

The template waveform of the m th correlator is given by

$$h_m(t) = \sqrt{\frac{\hat{N}_s}{E_s}} a_j^{(1)} p(t - c_j^{(1)} T_c - m\delta) \quad (8)$$

where $S_{\text{conv}} = (-1)^{n_i^{(1)}} \hat{N}_s A_1 R(0)$ is the correlator output of the desired transmitted signal. I_{conv} is the correlator output coming from other $K - 1$ users' signals and is called MAI. The MAI can be described as $I_{\text{conv}} = \sum_{k=2}^K A_k I_{\text{conv}}^{(k)}$, where $I_{\text{conv}}^{(k)}$ is the MAI caused by the k th user. n_{conv} is a Gaussian random variable with zero mean and variance $\sigma_{n_{\text{conv}}}^2 = N_0 \hat{N}_s^2 R(0)/2E_s$. Based on the

maximum likelihood decision rule for AWGN channel [5], the receiver of the desired user computes a bank of M correlators' outputs, $\{r_m\}_{m=0}^{M-1}$ in (7), and then chooses the index corresponding to the largest absolute value of the correlator's output as the estimate of the message symbol $\hat{m}_i^{(1)}$:

$$\hat{m}^{(1)} = \arg \max_{m \in \{0,1,\dots,N/2-1\}} |r_m| \quad (9)$$

as well as

$$\hat{n}^{(1)} = \begin{cases} 1, & r_{\hat{m}^{(1)}} < 0 \\ 0, & r_{\hat{m}^{(1)}} > 0 \end{cases} \quad (10)$$

Consider the receiver structure of the proposed TH/DS system shown in Figure 3. The output of the m th correlator in the j th frame duration is

$$e_{mj} = \int_{jT_f}^{(j+1)T_f} r(t)h_{m \oplus c_j^{(1)}}(t-jT_f)dt = \begin{cases} S_{j,\text{pro}} + I_{j,\text{pro}} + n_{j,\text{pro}}, & m = m_i^{(1)} \\ I_{j,\text{pro}} + n_{j,\text{pro}}, & m \neq m_i^{(1)} \end{cases} \quad (11)$$

where $n_{j,\text{pro}}$ is i.i.d. Gaussian noise with zero mean and variance $\sigma_{n_{j,\text{pro}}}^2 = N_0 N_s R(0)/2E_s$. The template waveform of the m th correlator is expressed as

$$h_{m \oplus c_j^{(1)}}(t) = \sqrt{\frac{N_s}{E_s}} a_j^{(1)} p(t - (m \oplus c_j^{(1)}) \delta) \quad (12)$$

where $S_{\text{conv}} = (-1)^{n_i^{(1)}} \hat{N}_s A_1 R(0)$ is the $m_i^{(1)}$ th correlator's output; $S_{j,\text{pro}} = (-1)^{n_i^{(1)}} A_1 R(0)$ is the desired

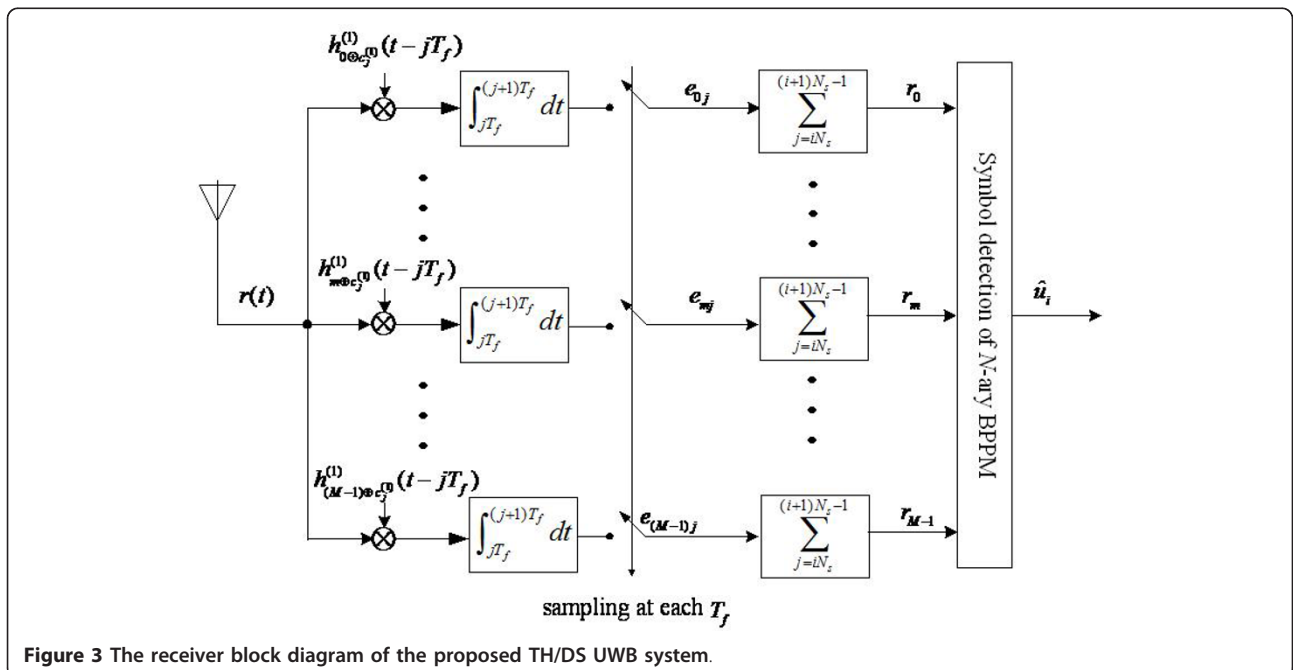


Figure 3 The receiver block diagram of the proposed TH/DS UWB system.

component corresponding to the data symbol $m_i^{(1)}$, and

$I_{j,\text{pro}} = \sum_{k=2}^K A_k I_{j,\text{pro}}^{(k)}$ where $I_{j,\text{pro}}^{(k)}$ is the MAI from the k th user. Completing the combining process, the m th decision variable can then be acquired as

$$r_m = \sqrt{\frac{N_s}{E_s}} \sum_{j=iN_s}^{(i+1)N_s-1} a_j^{(1)} \int_{jT_f}^{(j+1)T_f} r(t) p(t - jT_f - (m \oplus c_j^{(1)}) \delta) dt \quad (13)$$

$$= \begin{cases} S_{\text{pro}} + I_{\text{pro}} + n_{\text{pro}}, & m = m_i^{(1)} \\ I_{\text{pro}} + n_{\text{pro}}, & m \neq m_i^{(1)} \end{cases}$$

where n_{pro} is Gaussian random noise with zero mean and variance $\sigma_{n_{\text{pro}}}^2 = N_0 N_s^2 R(0) / 2E_s$.

$S_{\text{pro}} = (-1)^{n_i^{(1)}} A_1 N_s R(0)$ is the desired component corresponding to the data symbol $m_i^{(1)}$, and I_{pro} is the total MAI caused by the $K - 1$ interfering users,

$$I_{\text{pro}} = \sum_{j=iN_s}^{(i+1)N_s-1} I_{j,\text{pro}} = \sum_{j=iN_s}^{(i+1)N_s-1} \sum_{k=2}^K A_k I_{j,\text{pro}}^{(k)} \quad (14)$$

Let $\tau_k = \alpha_k T_f + \Delta_k$ and $\Delta_k = \beta_k T_p + \gamma_k$ where α_k is the discrete uniformly distributed r.v. in $\{0, 1, \dots, N_s - 1\}$; β_k is the discrete uniformly distributed r.v. in $\{0, 1, \dots, M - 1\}$; and γ_k is the continuous uniformly distributed r.v. in one pulse duration, i.e., $0 \leq \gamma_k < T_p$ [4]. Hence, we can obtain $I_{j,\text{pro}}^{(k)}$ as follows:

$$I_{j,\text{pro}}^{(k)} = \int_{jT_f}^{(j+1)T_f} a_j^{(1)} \sum_{q=iN_s}^{(i+1)N_s-1} (-1)^{n_q^{(k)}} a_q^{(k)} p(t - qT_f - b_q^{(k)} \delta - \tau_k) p(t - jT_f - (m \oplus c_j^{(1)}) \delta) dt \quad (15)$$

$$= a_j^{(1)} a_{j-\alpha_k}^{(k)} (-1)^{n_{j-\alpha_k}^{(k)}} R(b_{j-\alpha_k}^{(k)} T_p + \beta_k T_p + \gamma_k - (m \oplus c_j^{(1)}) T_p - T_f) \\ + a_j^{(1)} a_{j-\alpha_k}^{(k)} (-1)^{n_{j-\alpha_k}^{(k)}} R(b_{j-\alpha_k}^{(k)} T_p + \beta_k T_p + \gamma_k - (m \oplus c_j^{(1)}) T_p)$$

and can be rewritten as

$$I_{j,\text{pro}}^{(k)} = U_j^{(k)} \widehat{R}_p(\gamma_k) \widehat{\Gamma}_j(\Delta_k) + V_j^{(k)} R_p(\gamma_k) \Gamma_j(\Delta_k) \quad (16)$$

where $\widehat{R}_p(\gamma_k) = \int_{\gamma_k}^{T_p} p(t) p(t - \gamma_k) dt$ and $U_j^{(k)}$, $V_j^{(k)}$ and $\Gamma_j(\Delta_k)$ are the discrete uniformly distributed r.v.s in $\{-1, +1\}$ because the polarity codes $\mathbf{a}^{(k)}$ and the message symbol $n^{(k)}$ of the user k are assumed to be random and equally likely. $\Gamma_j(\Delta_k)$ and $\widehat{\Gamma}_j(\Delta_k)$ can be expressed as follows:

$$\widehat{\Gamma}_j(\Delta_k) = \begin{cases} 1; & \text{if } 0 \leq k_2 - k_1 < T_p \text{ or } 0 \leq k_3 - k_1 < T_p \\ 0; & \text{otherwise} \end{cases} \quad (17)$$

$$\Gamma_j(\Delta_k) = \begin{cases} 1; & \text{if } 0 \leq k_1 - k_2 < T_p \text{ or } 0 \leq k_1 - k_3 < T_p \\ 0; & \text{otherwise} \end{cases} \quad (18)$$

where $k_1 = (m \oplus c_j^{(1)}) T_p$, $k_2 = \Delta_k + b_{j-\alpha_k}^{(k)} T_p$, and $k_3 = \Delta_k + b_{j-\alpha_k-1}^{(k)} T_p - T_f$. The i th data symbol of the k th user $m_i^{(k)}$ is assumed to be an uniformly distributed r.v. in the range of $0 \leq m_i^{(k)} \leq M - 1$ and each element $c_j^{(k)}$ of the random TH code utilized by the k th user in the j th frame period is assumed to be an uniformly distributed r.v. with $c_j^{(k)} \in G = \{0, 1, 2, \dots, Q - 1\}$. Therefore, $b_j^{(k)} = m_i^{(k)} \oplus c_j^{(k)}$ is an uniformly distributed r.v. with $b_j^{(k)} \in F$. The probability density function (PDF) of $I_{j,\text{pro}}^{(k)}$ conditioned on γ_k can be described as

$$f_{I_{j,\text{pro}}^{(k)} | \gamma_k, U_j^{(k)}, V_j^{(k)}}(i) = \frac{1}{Q} \delta_D(i - U_j^{(k)} \widehat{R}(\gamma_k)) + \frac{1}{Q} \delta_D(i - V_j^{(k)} R(\gamma_k)) + \frac{Q-2}{Q} \delta_D(i) \quad (19)$$

where δ_D is the Dirac delta function. Therefore, the conditional CF of $I_{j,\text{pro}}^{(k)}$ can be obtained as obtained as

$$\Phi_{I_{j,\text{pro}}^{(k)} | \gamma_k}(\omega) = \frac{1}{Q} \cos(\omega R(\gamma_k)) + \frac{1}{Q} \cos(\omega \widehat{R}(\gamma_k)) + \frac{Q-2}{Q} \quad (20)$$

The interferences $I_{j,\text{pro}}^{(k)}$ are independent of each other because each element of the user's TH code $\mathbf{c}^{(k)}$ is randomly and independently selected from the set G . Hence,

$$\Phi_{I_{\text{pro}}^{(k)} | \gamma_k}(\omega) = \left[\frac{1}{Q} \cos(\omega R(\gamma_k)) + \frac{1}{Q} \cos(\omega \widehat{R}(\gamma_k)) + \frac{Q-2}{Q} \right]^{N_s} \quad (21)$$

and we then obtain

$$\Phi_{I_{\text{pro}}^{(k)}}(\omega) = \frac{1}{T_p} \int_0^{T_p} \left[\frac{1}{Q} \cos(\omega R(\gamma_k)) + \frac{1}{Q} \cos(\omega \widehat{R}(\gamma_k)) + \frac{Q-2}{Q} \right]^{N_s} d\gamma_k \quad (22)$$

$$\Phi_{I_{\text{pro}}}(\omega) = \prod_{k=2}^K \Phi_{I_{\text{pro}}^{(k)}}(A_k \omega) \quad (23)$$

It is worthy to note that the CF of the MAI component for each correlator's output of the proposed TH/DS receiver is different from that of the conventional TH/DS system which has been shown in [3].

3.1 Symbol error rate

Let the i th data symbol of the desired user be $u_i^{(1)} = (m_i^{(1)}, n_i^{(1)}) = (0, 0)$. According to our derived CF of the MAI component for the correlator's output of the proposed TH/DS receiver in (23), the average SER of

the N -ary biorthogonal modulation has been expressed and calculated as [5]:

$$P_e = 1 - \int_0^{+\infty} P(|r_1| \leq \mu, |r_2| \leq \mu, \dots, |r_{N/2-1}| \leq \mu | \mu) f_{r_0}(\mu) du$$

The decision statistics of the combining correlators' outputs $\{r_m\}_{m=0}^{N/2-1}$ are assumed to be independent [2,3,17-21]. Hence, the SER of the proposed system is

$$\begin{aligned} P_e &= 1 - \int_0^{+\infty} [P(|r_1| \leq u | u)]^{N/2-1} f_{r_0}(u) du \\ &= 1 - \int_0^{+\infty} [F_{r_1}(u) - F_{r_1}(-u)]^{N/2-1} f_{r_0}(u) du \end{aligned} \quad (24)$$

where $F_{r_1}(u)$ is the CDF of r_1 . The first decision variable is $r_0 = A_1 N_s R(0) + I + n$, and the other $M - 1$ decision variables are $\{r_m\}_{m=0}^{M-1} = I + n$. Therefore, (24) can be rewritten as

$$P_e = 1 - \int_0^{+\infty} [F_{r_1}(u) - F_{r_1}(-u)]^{N/2-1} f_{r_1}(u - A_1 N_s R(0)) du \quad (25)$$

As the MAI and AWGN are assumed to be mutually independent, we obtain the CF of r_1 as $\Phi_{r_1}(\omega) = \Phi_I(\omega) \Phi_n(\omega)$, where the CF of the AWGN is $\Phi_n(\omega) = e^{-\sigma_{\text{pro}}^2 \omega^2 / 2}$. Hence, the PDF of r_1 can be acquired as

$$f_{r_1}(u) = \frac{1}{\pi} \int_0^{+\infty} \Phi_{r_1}(\omega) \cos(\omega u) d\omega \quad (26)$$

Applying the relationship between the CF and CDF [12-14], we have

$$F_{r_1}(u) = \frac{1}{2} + \frac{1}{\pi} \int_0^{+\infty} \Phi_{r_1}(\omega) \frac{\sin(\omega u)}{\omega} d\omega \quad (27)$$

If all $M - 1$ erroneous symbols are equally likely chosen, then the corresponding BER is $P_b = M \cdot P_e / [2 \cdot (M - 1)]$ [5].

4 Simulation results

The pulse width $T_p = 0.7$ ns is selected for the systems. Assuming that the system bandwidth and the data rate are fixed at $T_b/T_p = 64$, the BER performances of the conventional and the proposed TH/DS systems are respectively illustrated in Figure 4 with $K = 16$, and in Figures 5 and 6 with $K = 24$. Figure 4 shows the BER performances of the conventional and the proposed TH/DS systems using different modulation levels of BPPM with a fixed number of frames. In Figure 5, the SER performances of the conventional and the proposed TH/DS systems employing the same modulation level $\hat{N}(N) = 16$ are examined. It is

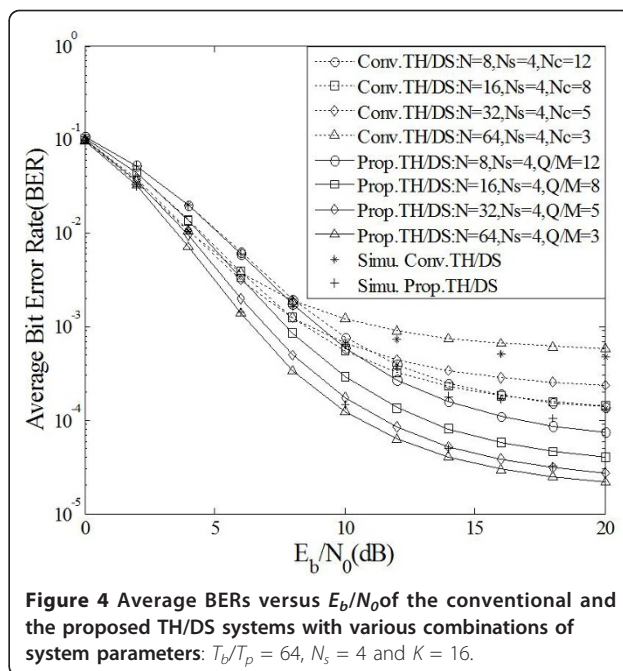


Figure 4 Average BERs versus E_b/N_0 of the conventional and the proposed TH/DS systems with various combinations of system parameters: $T_b/T_p = 64$, $N_s = 4$ and $K = 16$.

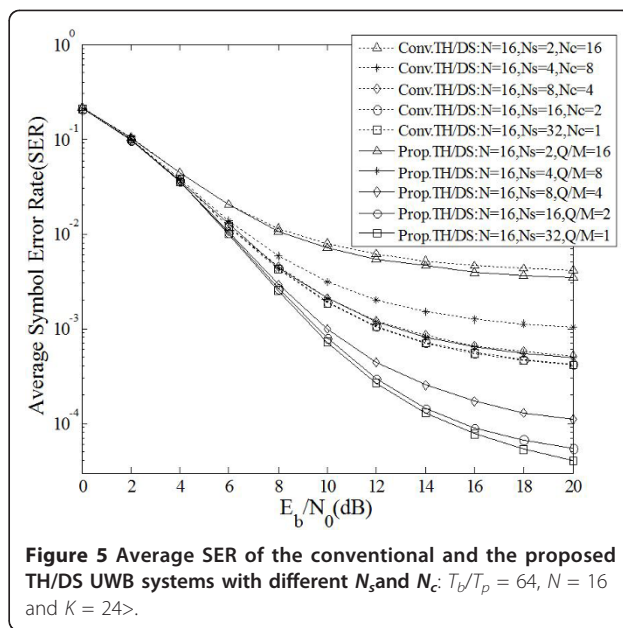
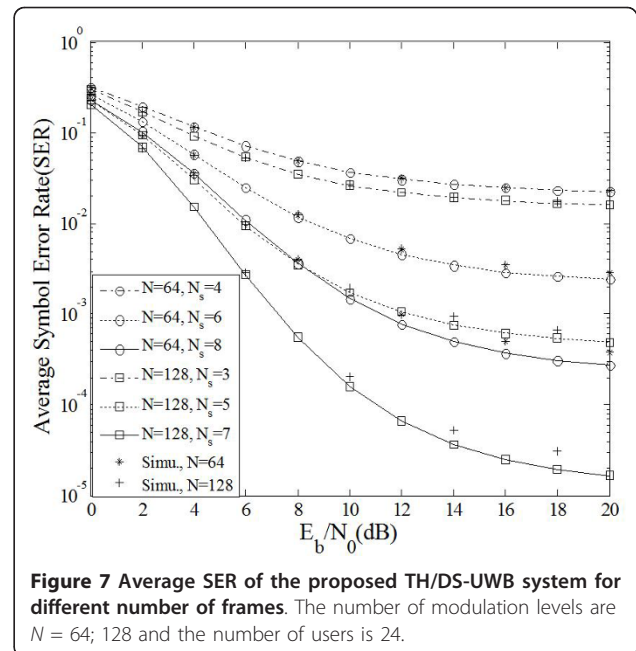
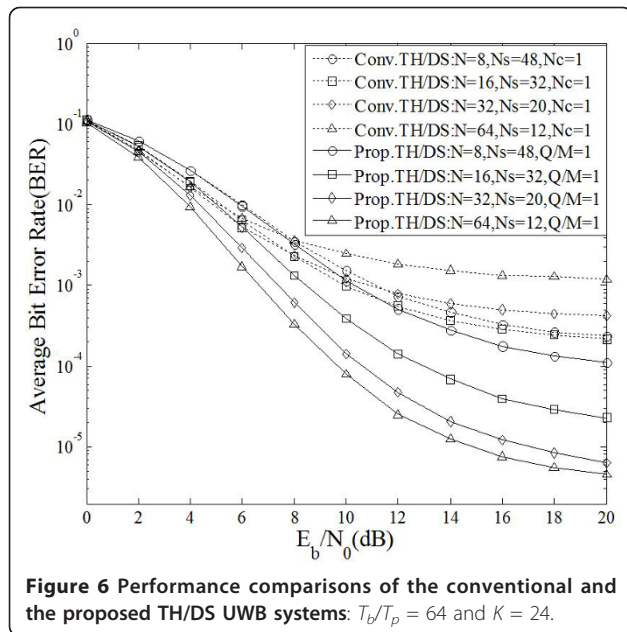


Figure 5 Average SER of the conventional and the proposed TH/DS UWB systems with different N_s and N_c : $T_b/T_p = 64$, $N = 16$ and $K = 24$.

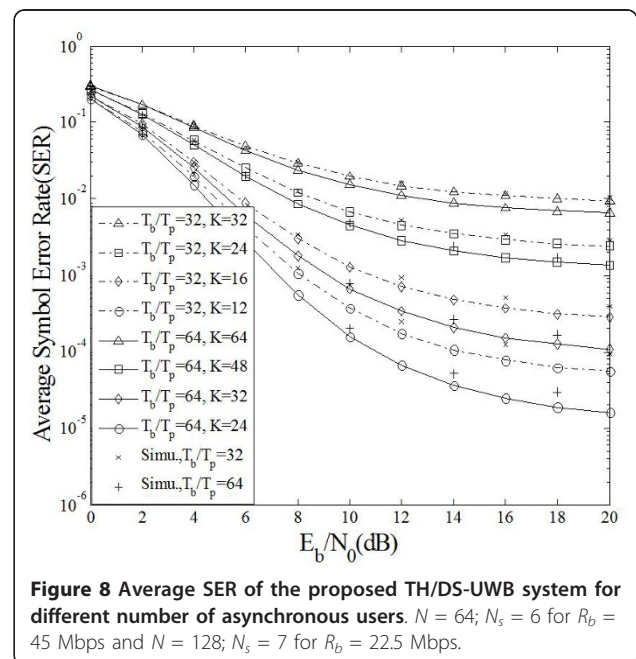


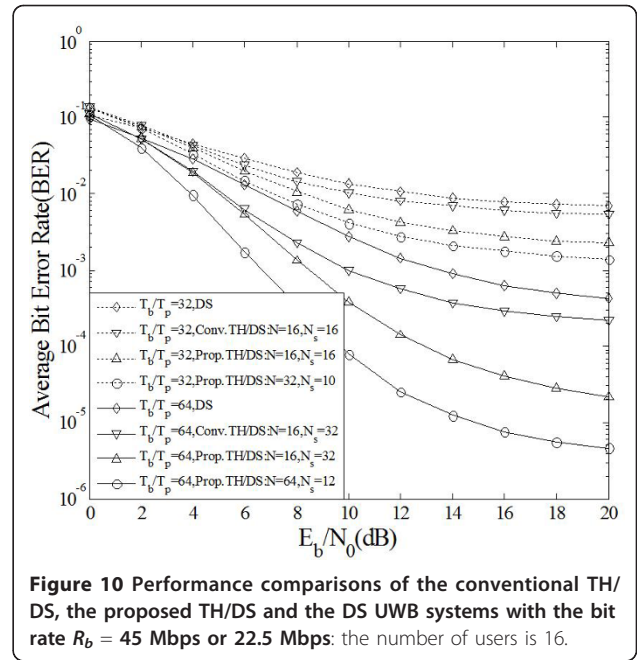
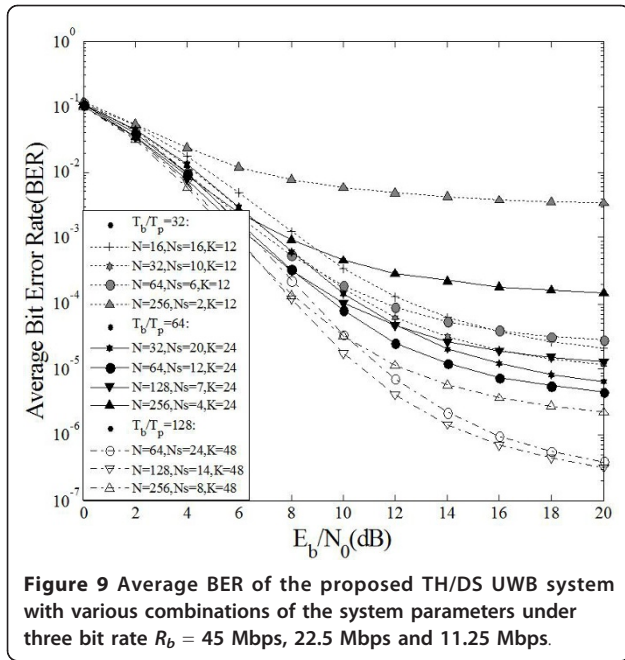
selected, which can provide the largest number of frames N_s based on (6), the proposed TH/DS systems still utilize the whole frame duration to carry out the TH process and further reduce the impact of MAI. Figure 6 demonstrates the performance comparisons between the conventional and the proposed TH/DS systems employing several modulation levels accompanied with the largest number of frames used. From Figures 4, 5, and 6, the performance of the conventional TH/DS system becomes worse with the modulation level $\hat{N} > 16$. However, applying larger modulation level in the proposed TH/DS system still provides lower average error probability. Even though smaller modulation levels employed in the conventional and the proposed TH/DS systems result in almost the same system complexities, the proposed TH/DS system still outperforms the conventional TH/DS scheme.

To achieve the best performance of the proposed TH/DS system, the number of available pulse slots $Q = M$ is chosen in the following numerical results and simulations. The analytic SERs of the proposed system using different N_s (the levels of time diversity) are presented in Figure 7. As expected, the performance of the proposed system becomes better as the number of frame is larger. It is noted that the performance gain is obtained at the cost of the reduction of the transmission (bit) rate. In Figure 8, the impact of the number of users on the performance of the proposed system is investigated. When we consider the fixed system throughput KR_b in Figure 8, it is shown that the proposed system applying larger $T_b/T_p (= 64)$ and modulation level ($N = 128$) can

provide better performance. From these aforementioned performance curves, the analytic results are consistent with the simulations.

Considering the cases of fixed ratios of $T_b/T_p = 32, 64,$ and 128 (corresponding to bit rates $R_b = 45; 22.5$ and 11.25 Mbps, respectively), the analytic SER performances of the proposed system with different number of modulation levels N are depicted in Figure 9. According to (6), the number of frames (the level of time



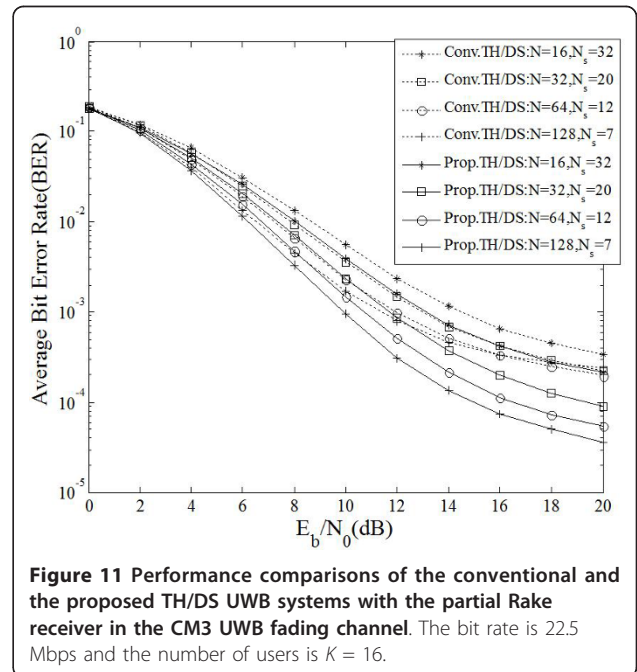


diversity) N_B decreases as the number of modulation levels increases. To make fair performance comparison, the same system throughput, i.e., $KR_b = 540$ Mbps, is considered. Consequently, the numbers of users are $K = 12, 24,$ and 48 are utilized corresponding to $T_b/T_p = 32, 64$ and 128 , respectively. Observing the results in Figure 9, for a specific T_b/T_p , there is an optimum N that achieves minimum SER. The optimal N is equal to T_b/T_p . This result is similar to that of the frequency-hopping MA systems in [7]. In addition, the proposed system combined with larger $T_b/T_p (= N)$ can provide better SER performance.

In Figure 10, the BERs of the conventional TH/DS-UWB, the proposed TH/DS-UWB, and the DS-UWB systems with the total number of users $K = 16$ are examined. The cases of $T_b/T_p = 32$ and 64 in [13] are considered. When the bit rate is $R_b = 45$ Mbps, the system parameters of the conventional TH/DS system are $\hat{N} = 16, \hat{N}_s = 16$ and $\hat{N}_c = 1$. On the other hand, the parameters of $N = 16$ and 32 ($N_s = 16$ and 10) are selected in the proposed TH/DS system. In cases of $R_b = 22.5$ Mbps, the optimal system parameters of the conventional TH/DS system which was shown in Figure 6 are $\hat{N} = 16, \hat{N}_s = 32$ and $\hat{N}_c = 1$. For the proposed TH/DS system, the parameters of $N = 16$ and 64 ($N_s = 32$ and 12) are chosen. This figure demonstrates that the performance of the proposed TH/DS system is better than that of the conventional TH/DS system even though the same system complexities (i.e., the same modulation levels) are considered. It is worthy to note that both the conventional and the proposed TH/DS-

UWB systems employing non-binary BPPM are illustrated to outperform the DS-UWB system which was shown to provide the best system performance in all of the binary-modulated UWB systems [13].

Finally, the simulations of the conventional and the proposed TH/DS systems are conducted in the specific UWB multipath channel model, namely, CM3 fading channel. The partial RAKE (PRAKE) receiver that



combines the first 20 resolvable multipaths is employed. Perfect channel estimation is assumed, and the maximum ratio combining is applied in the receiver. The BER performances of the examined TH/DS systems in CM3 fading channel are presented in Figure 11, in which all of the system parameters adopted are the same as those used in Figure 10. It is observed that the proposed TH/DS scheme performs better than the conventional TH/DS system.

5 Conclusions

A new TH/DS UWB system employing the whole frame to carry out TH and N -ary BPPM is proposed in this article. According to the derived CF expression of the MAI, a simple SER analysis of the proposed TH/DS system using N -ary BPPM is obtained in the presence of asynchronous MAI and AWGN. The proposed SER performance analysis is shown to be consistent with the simulations. From the simulation results, the proposed TH/DS system is shown to outperform both the conventional TH/DS system and the DS UWB systems.

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