N-ary Biorthogonal Pulse Position Shape Modulation for Hybrid TH/DS Multiple Access UWB System

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***Abstract*—A N-ary biorthogonal pulse position shape modulation (BPPSM) for hybrid time-hopping/direct-sequence (TH/DS) multiple access ultra-wideband (UWB) system is proposed and analyzed in this paper. The characteristic function (CHF) of the multiple access interference (MAI) is derived and, accordingly, the average symbol error rate (SER) of the proposed system can be accurately evaluated. Simulation are carried out to verify the analytical results in additive white Gaussian noise (AWGN) channel and to illustrate the system performance in realistic UWB fading channels. As increasing the number of adopting pulses, the proposed TH/DS N-ary BPPSM system can provide better SER performance compared with the TH/DS N-ary BPPM scheme. Given the constraints of fixed bit rate and signal bandwidth, the impact of adjusting various system parameters on the system performance is also investigated.**

I. Introduction

[1]Using extremely large bandwidth of the transmitted signal, the UWB technology is suitable to provide multiple access capability and counteract multiple access interference (MAI) [1]. Impulse radio (IR) technique which transmits a train of impulses (termed monocycles) with very short duration to deliver message symbols has been widely applied in UWB communication. Typically, the pulse-based modulation schemes which are usually employed in the IR UWB systems are the pulse amplitude modulation (PAM), the pulse position modulation (PPM), and the pulse position amplitude modulation (PPAM). In PPAM modulation, both the position and the amplitude of impulses are used to denote the data message [10]-[11]. A biorthogonal PPM (BPPM) [11] has the antipolar amplitudes of the modulated signals and can provide the best performance compared with other PPAM signaling with multi-level amplitudes of the modulated signals. For these mentioned modulations, a single type of impulse called as the second order Gaussian monocycle has been widely used to deliver the message symbols.

Recently, some design algorithms were proposed to produce several sets of the orthonormal pulses such as Prolate Spheroidal Wave Functions (PSWF) [13] or Modified Hermite (MH) polynomials [14] [15]. These orthonormal (MH or PSFW) pulses, which satisfy the spectral mask requested by the Federal Communication Commission (FCC), are short in time and have a constant pulse width, irrespective of the pulse's order. When we have a set of the orthonormal pulses, the pulse shape modulation (PSM) is an alternative modulation scheme in which the data message is conveyed in the shape of impulses [16]. To achieve the larger modulation level for the pulse-based modulation, $M(=PQ)$-ary pulse position shape modulation (PPSM) which consists of P-ary PPM and Q-ary PSM modulation was introduced [17]. A biorthogonal PPSM (BPPSM), which is an antipodal version of PPSM signals, can carry one more bit in the amplitudes of impulse [17]. Furthermore, BPPSM signaling has been shown to provide better performance compared with BPPM and BPSM schemes.

In order to reduce the impact of multiple access interference on the system performance, the time hopping (TH) scheme is widely employed as the MA techniques in the IR UWB systems. Recently, in the binary modulations TH-UWB system, the usage of the random polarities in the pulse's amplitudes (called a coded system in [6]) not only remove the discrete spectral of the transmitted signal, but also provide the better performance compared with uncoded system [4]-[6]. The advantage of using random polarity is also confirmed for the nonbinary (N-ary) modulation system [12]. Therefore, in the paper, a N-ary BPPSM TH system including the random polarities in the pulse's amplitudes (namely the hybrid TH/DS N-ary BPPSM UWB system) is proposed and the accurate SER performance of the proposed system is also calculated.

In asynchronous MA scenarios, the performance evaluations of the TH-UWB systems using nonbinary modulation schemes have been investigated in [7]-[9],[10]-[11],[15]-[16]. Regarding to the M-ary PPM [7], N-ary BPPM [10][11] and N-ary BPPSM [17], the system performances of these TH UWB systems were analyzed based on that the statistics of MAIs are assumed by Gaussian distribution. However, the Gaussian approximation (GA) fails to model the distribution of MAIs precisely due to the impulse-like in the distribution of MAI. Recently, using the analytical frameworks based on the characteristic functions (CFH) techniques, the accurate performance analyses of binary PPM TH, M-ary PPM TH and N-ary BPPM TH/DS UWB systems were presented in [3], [9] and [12], respectively. However, to the best of our knowledge, the CFH analytical scheme has not been applied to analyze the N-ary BPSM or N-ary BPPSM in the MA TH-UWB systems.

In the following sections, the N-ary BPPSM applied in hybrid TH/DS system is introduced. Based on the derived

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CHF of MAI, the SER performance of the proposed system is accurately analyzed in Section 3. Some numerical examples validated by the simulations are presented in Section 4. Finally, the conclusion is provided in the last section.

II. System Model and Definitions

At the transmitter of the proposed system, a data bit stream of rate R_b bits/s is mapped into an N-ary BPPSM symbol sequence of rate R_s symbols/s, where $R_s = 1/T_s = 1/vT_b$, and $v = \log_2 N$ is the number of bits per symbol. Based on the signal structures of the TH systems, each symbol duration T_s is partitioned into N_s frames with duration T_f, i.e., $T_s = N_s T_f$, and each frame interval is divided into N_c TH slots with duration T_c, i.e. $T_f = N_c T_c$. A $N(= 2M)$-ary BPPSM modulated waveform for the user k in the ith symbol interval is expressed as

$$s^{(k)}(t) = \sum_i (-1)^{r_i^{(k)}} b^{(k)}_{q_i^{(k)}}(t - iT_s - p_i^{(k)}\delta) \qquad (1)$$

where t is time index, $p_i^{(k)} \in \{0, 1, 2, ..., P-1\}$, $q_i^{(k)} \in \{0, 1, 2, ..., Q-1\}$, and $r_i^{(k)}$, $r_i^{(k)} \in \{0, 1\}$, respectively denote $v - u - 1$ bits, u bits, and one bit that are all included in the ith symbol of the BPPSM signals. According to the N-ary BPPSM, the values of $p_i^{(k)}$, $q_i^{(k)}$, and $r_i^{(k)}$ are used to decide the position, shape, and polarity of a modulated impulse. Consequently, a combined v-bit ($v = \log_2 N$) message symbol, $u_i^{(k)} = (p_i^{(k)}, q_i^{(k)}, r_i^{(k)})$, is produced in the ith symbol duration. Afterward, the symbol-level transmitted waveform of the kth user in (1) is given as

$$b^{(k)}_{q_i^{(k)}}(t) = \sqrt{\frac{E_s}{N_s}} \sum_{l=0}^{N_s-1} a^{(k)}_{l,q_i^{(k)}} w_{q_i^{(k)}}(t - lT_f - c^{(k)}_{l,q_i^{(k)}} T_c) \qquad (2)$$

where E_s is the average symbol energy of each user's signal, N_s is the number of transmitted pulses (frames) in one symbol duration. $c^{(k)}_{l,q_i^{(k)}} \in \{0, 1, 2, ..., N_c - 1\}$ is the lth element of the kth user's time hopping (TH) code used to randomize the position of the modulated impulse in lth frame time. $a^{(k)}_{l,q_i^{(k)}} \in \{-1, 1\}$ is the lth element of the kth user's polarity code (or called DS spreading code) used to randomize the polarity of the modulated impulse in lth frame time. To mitigate the effect of MAI on the system performance, the kth user is assigned a specific random TH code $\mathbf{c}_q^{(k)} = (c^{(k)}_{0,q}, c^{(k)}_{1,q}, ..., c^{(k)}_{N_s-1,q})$ and a random polarity (DS) code $\mathbf{a}_q^{(k)} = (a^{(k)}_{0,q}, a^{(k)}_{1,q}, ..., a^{(k)}_{N_s-1,q})$. Due to the assumption of orthogonal P-ary PPM signaling, we set the time shift between two adjacent PPM signals equal to the pulse width, i.e., $\delta = T_w$. Therefore, the interval of one chip (T_c) is defined as PT_w. The well-known modified Hermite pulses (MHPs) have been widely applied to the PSM in previous literatures. The nth order of the MHP was introduced in [14]-[15] and is written as

$$\widehat{w}_n(t) = k_n(-\tau)^n e^{\frac{t^2}{4\tau_p^2}} \frac{d^{\,n}}{dt^{\,n}} \left(e^{-\frac{t^2}{2\tau_p^2}} \right) \qquad (3)$$

where τ_p denotes a time-scaling factor of the pulse width and $k_n = \sqrt{\frac{1}{n!\tau\sqrt{2\pi}}}$ is a coefficient used to normalize the energy of each MHP, i.e. $\int_{-\infty}^{\infty} \widehat{w}_n^2(t)dt = 1$. The correlation function of MHPs between a time-shifted pulse $\widehat{w}_m(t - x)$ and the reference pulse $\widehat{w}_n(t)$ is defined as

$$R_{n,m}(x) = \int_{-\infty}^{\infty} \widehat{w}_m(t - x)\, \widehat{w}_n(t)\, dt \qquad (4)$$

Accordingly, in this paper, a set of Q normalized Hermite pulses (MHP),$\{w_q(t) = \widehat{w}_{n+1}(t)\}_{q=0}^{Q-1}$ is adopted as the orthonomal waveforms.

Assume that N_u users' signals are transmitted asynchronously through an AWGN channel, the received signal is expressed as

$$r(t) = \sum_{k=1}^{N_u} s^{(k)}(t - \tau_k) + n(t) \qquad (5)$$

where $n(t)$ is the AWGN with zero mean and two-sided power spectral density $N_0/2$. Let $s^{(1)}(t)$ be the received signal of the desired user and $u_i^{(1)} = (p_i^{(1)}, q_i^{(1)}, r_i^{(1)})$ is the desired message symbol in the ith symbol duration. It is assumed that the desired signal is perfectly synchronized and coherently detected at the receiver, i.e. $\tau_1 = 0$. τ_k represents asynchronous time shift of the kth user's received signal and is assumed to be uniformly distributed random variable (RV) over one symbol duration, i.e. $[0, N_s T_f]$ [2][9]. The required bandwidth of the transmitted signal is assumed to be $1/T_w$ approximately. Since the symbol interval is $T_s = vT_b = N_s N_c P T_w$, the ratio of T_b and T_w is obtained as

$$\frac{T_b}{T_w} = \frac{N_s N_c P}{\log_2 N} \qquad (6)$$

where $N = 2PQ$ is the modulation level of BPPSM signal. Note that the transmission bit rate ($R_b = 1/T_b$) of the proposed system decreases as the ratio T_b/T_w increases.

III. Symbol Error Rate of the System

A. Characteristic Function of MAI

To detect the ith data symbol of the desired user $u_i^{(1)}$, the received signal is correlated with PQ orthogonal template waveforms to obtain $PQ(= N/2)$ decision variables $\{r_{m,n}\}_{m=0,n=0}^{P-1,Q-1}$ which can be expressed as

$$\begin{aligned} r_{m,n} &= \sum_{j=iN_s}^{(i+1)N_s-1} \int_{jT_f}^{(j+1)T_f} r(t) h_{m,n}(t) dt \\ &= \begin{cases} S_{m,n} + I_{m,n} + N_{m,n}, & m = p_i^{(1)}, n = q_i^{(1)} \\ I_{m,n} + N_{m,n}, & m \neq p_i^{(1)}, n \neq q_i^{(1)} \end{cases} \end{aligned} \qquad (7)$$

where the template waveform of the (m, n)th correlator is given by

$$h_{m,n}(t) = \sqrt{\frac{N_s}{E_s}} a^{(1)}_{j,n} w_n(t - jT_f - c^{(1)}_{j,n} T_c - m\delta) \qquad (8)$$

At the (m, n)th correlator's output, $N_{m,n}$ is the noise component which is Gaussian random variable (RV) with zero mean and variance $\sigma_N^2 = N_0 N_s^2 R(0)/2E_s$. $S_{m,n}$ in (7) is the desired signal which is corresponding to the desired message symbol $(p_i^{(1)}, q_i^{(1)}, r_i^{(1)})$ and given as $S_{m,n} =$

$(-1)^{r_i^{(1)}} N_s R_{n,n}(0)$, where the orthogonal property of any two modified Hermite pulses $w_i(t)$ and $w_j(t)$ is applied, i.e., $R_{i,j}(0) = 0$, $\forall i \neq j$. The total MAI component $I_{m,n}$ that is produced from $N_u - 1$ interference users can be expressed as

$$I_{m,n} = \sum_{k=2}^{N_u} I_{m,n}^{(k)} = \sum_{k=2}^{N_u} \sum_{j=iN_s}^{(i+1)N_s-1} I_{m,n,j}^{(k)} \tag{9}$$

According to the notations employed to model the asynchronous (random) time delay of the kth user for binary modulation [2], we define $\tau_k = \alpha_k T_f + \Delta_k$. Since these asynchronous time delays, $\{\tau_k\}_{k=2}^{N_u}$, are modeled as the uniformly distributed RVs over one symbol interval, α_k is a discrete uniformly distributed RV on $\{0, 1, ..., N_s - 1\}$, and Δ_k is a continuous uniformly distributed RV over one frame interval, i.e. $0 \leq \Delta_k < T_f$. Afterward, only the first message symbol of the desired user $u_0^{(1)} = (p_0^{(1)}, q_0^{(1)}, r_0^{(1)})$ is considered in the following. After some mathematical manipulations, the signal of the kth interfering user appeared on the (m, n)th correlator's output in the jth frame duration can be derived as

$$\begin{aligned}
I_{m,n,j}^{(k)} &= (-1)^{r^{(k,j-1)}} a_{j-\alpha_k-1,q^{(k,j-1)}}^{(k)} a_{j,n}^{(1)} \\
&\quad \times R_{n,q^{(k,j-1)}}((c_{j-\alpha_k-1,q^{(k,j-1)}}^{(k)} - c_{j,n}^{(1)})T_c \\
&\qquad + \Delta_k + (p^{(k,j-1)} - m)\delta - T_f) \\
&\quad + (-1)^{r^{(k,j)}} a_{j-\alpha_k,q^{(k,j)}}^{(k)} a_{j,n}^{(1)} \\
&\times R_{n,q^{(k,j)}}((c_{j-\alpha_k,q^{(k,j)}}^{(k)} - c_{j,n}^{(1)})T_c + \Delta_k + (p^{(k,j)} - m)\delta).
\end{aligned} \tag{10}$$

where only two (previous $u_{-1}^{(k)}$ and current $u_0^{(k)}$) message symbols of the kth interference user are hitting to the first message symbol of the desired user. Therefore, we define

$$(p^{(k,j)}, q^{(k,j)}, r^{(k,j)}) \triangleq \begin{cases} (p_{-1}^{(k)}, q_{-1}^{(k)}, r_{-1}^{(k)}), & j < \alpha_k \\ (p_0^{(k)}, q_0^{(k)}, r_0^{(k)}), & j \geq \alpha_k \end{cases} \tag{11}$$

Since the received signals of the interference users come from different transmission paths, $\{I_{m,n}^{(k)}\}_{k=2}^{N_u}$ in (9) are assumed to be mutually independent random variables. Therefore, the CHF of the total MAI can be given by

$$\Phi_{I_{m,n}}(\omega) = \prod_{k=2}^{N_u} \Phi_{I_{m,n}^{(k)}}(\omega) \tag{12}$$

where the CHF of the MAI from the kth user can be expressed as

$$\Phi_{I_{m,n}^{(k)}}(\omega) = \frac{1}{N_s T_f} \int_0^{N_s T_f} \Phi_{I_{m,n}^{(k)}|\tau_k}(\omega) d\tau_k \tag{13}$$

In addition, the message symbols of the kth interference user, $p_i^{(k)}$, $q_i^{(k)}$ and $r_i^{(k)}$, are assumed to be equally likely RVs with $p_i^{(k)} \in \{0, 1, 2, ..., P-1\}$, $q_i^{(k)} \in \{0, 1, 2, ..., Q-1\}$ and $r_i^{(k)} \in \{0, 1\}$, respectively. Without loss of generality, the TH code of the desired user is assumed to be $c_{j,n}^{(1)} = 0$ for all j and n. Besides, each element of the random TH $(c_{j,q}^{(k)})$ and random DS code $(a_{j,q}^{(k)})$ of the kth user is assumed to be an uniformly distributed RV. Therefore, two MAI components, $U_{m,n}$ and $V_{m,n}$, are generated corresponding to the previous and current data symbols of the kth interference user, respectively. The CHFs of $U_{m,n}$ and $V_{m,n}$ conditioned on τ_k are respectively derived as

$$\Phi_{U_{m,n}|\tau_k}(\omega) = \frac{1}{PQ} \sum_{x=0}^{P-1} \sum_{y=0}^{Q-1} \left[\frac{1}{N_c} \sum_{h=0}^{N_c-1} \cos(\omega\phi_1) \bullet \cos(\omega\phi_2) \right]^{\alpha_k} \tag{14}$$

and

$$\Phi_{V_{m,n}|\tau_k}(\omega) = \frac{1}{PQ} \sum_{x=0}^{P-1} \sum_{y=0}^{Q-1} \left[\frac{1}{N_c} \sum_{h=0}^{N_c-1} \cos(\omega\phi_1) \bullet \cos(\omega\phi_2) \right]^{N_s-\alpha_k} \tag{15}$$

where $\phi_1 = R_{n,y}(hT_c + xT_p + \Delta_k - mT_p - T_f)$ and $\phi_2 = R_{n,y}(hT_c + xT_p + \Delta_k - mT_p)$. Accordingly, we can rewrite (13) as

$$\Phi_{I_{m,n}^{(k)}}(\omega) = \frac{1}{N_s T_f} \int_0^{N_s T_f} \Phi_{U_{m,n}|\tau_k}(\omega) \Phi_{V_{m,n}|\tau_k}(\omega) d\tau_k \tag{16}$$

Finally, based on the maximum likelihood decision rule for AWGN channel [19], the receiver of the desired user computes the PQ decision statistic $\{r_{p,q}\}_{p=0,q=0}^{P-1,Q-1}$ in (7) and then chooses the index corresponding to the largest of the absolute value for PQ decision variables as the estimate of the message symbol $\widehat{p}_i^{(1)}, \widehat{q}_i^{(1)}$,

$$\widehat{p}^{(1)}, \widehat{q}^{(1)} = \underset{p \in \{0,1,...,P-1\}, q \in \{0,1,...,Q-1\}}{\operatorname{argmax}} |r_{p,q}| \tag{17}$$

as well as

$$\widehat{r}^{(1)} = \begin{cases} 1, & r_{\widehat{p}^{(1)},\widehat{q}^{(1)}} < 0 \\ 0, & r_{\widehat{p}^{(1)},\widehat{q}^{(1)}} > 0 \end{cases} \tag{18}$$

B. Symbol Error Probability

Without loss of generality, we only consider the first data symbol, $u_0^{(1)} = (p_0^{(1)}, q_0^{(1)}, r_0^{(1)}) = (0, i, 0)$, transmitted from the desired user. To simplify the analysis of SER, the decision statistics of total $PQ(= M/2)$ correlators' outputs $\{r_{m,n}\}_{m=0,n=0}^{P-1,Q-1}$ are generally assumed to be independent [8]-[12]. According to our derived CHF of the MAI component at the correlator's outputs in (16) and the SER expression of the N-ary biorthogonal modulation in [12][19], the SER of the proposed system can be derived as

$$\begin{aligned}
SER = 1 - \frac{1}{Q} \sum_{i=0}^{Q-1} \int_0^{+\infty} &\left\{ \left[F_{r_{1,i}}(\lambda) - F_{r_{1,i}}(-\lambda) \right]^{P-1} \right. \\
&\left. \cdot \prod_{j \neq i}^{Q-1} \left[F_{r_{0,j}}(\lambda) - F_{r_{0,j}}(-\lambda) \right]^P \cdot f_{r_{0,i}}(\lambda) \right\} d\lambda
\end{aligned} \tag{19}$$

where $F_{r_{m,n}}(\lambda)$ is the cumulative distribution function (CDF) of $r_{m,n}$. Due to the assumptions of $(p_0^{(1)}, q_0^{(1)}, r_0^{(1)}) = (0, i, 0)$, only the output of $r_{0,i}$ has the desired signal component (i.e. $r_{0,i} = S_{0,i} + I_{0,i} + N_{0,i}$) and the other totally $PQ - 1$ correlators' outputs are $\{r_{m,n}\}_{m \neq 0, n \neq i} = I_{m,n} + N_{m,n}$. Since the MAI and the AWGN are assumed to be mutually independent, the CHF of $r_{0,j}$ and $r_{1,i}$ can be expressed as $\Phi_{r_{0,j}}(\omega) = \Phi_{I_{0,j}}(\omega)\Phi_N(\omega)$ and $\Phi_{r_{1,i}}(\omega) = \Phi_{I_{1,i}}(\omega)\Phi_N(\omega)$, respectively, where $\Phi_N(\omega) = e^{-\sigma_N^2 \omega^2/2}$ is the CHF of the

AWGN. In addition, the PDF of the symmetrical random variable, $r_{m,n}$, can be acquired as

$$f_{r_{m,n}}(\lambda) = \frac{1}{\pi}\int_0^{+\infty} \Phi_{r_{m,n}}(\omega)\cos(\omega\lambda)d\omega \tag{20}$$

By using the relationship between the CF and CDF [3][9], we obtain

$$F_{r_{m,n}}(\lambda) = \frac{1}{2} + \frac{1}{\pi}\int_0^{+\infty} \Phi_{r_{m,n}}(\omega)\frac{\sin(\omega\lambda)}{\omega}d\omega \tag{21}$$

Substituting the PDF and CDF of $r_{m,n}$ into (19), the analytical SER of the proposed system is finally obtained and the corresponding bit error rate (BER) is $BER = N\cdot SER/[2\cdot(N-1)]$ [19].

IV. Performance Results and Comparisons

An accurate SER of the proposed hybrid TH/DS UWB system that uses N-ary BPPSM and operates over AWGN channel is evaluated by (19). Besides, the simulations are implemented to validate the analytical results and also carried out in real UWB fading channels. Although a set of Q MPHs with the pulse width $T_w = 0.7$ns is adopted in this paper, other type (pulse shaping) of the monocycles can be also applied to evaluate the system performances if the correlation functions among those monocycles are provided.

The analytical SER performances of the proposed TH/DS BPPSM system with different number of frames (N_s) are shown in Fig. 1. The results indicate that the performance of the proposed system is improved by increasing the number of frames. According to (6), the system performance can be improved at the cost of decreasing the data (bit) rate. In Fig. 2, the SER calculations of the proposed system with different number of users (N_u) are illustrated. As expected, as the number of users N_u increases, the SER performance becomes worse. Observing from these performance curves, the analytical results are well consistent with those obtained by the simulations.

To fairly compare the system performances, a fixed ratio of $T_b/T_w = 32$ is employed in the following figures. The analytical BER performances of the proposed systems with different number of pulse positions (P) and pulse positions (Q) are illustrated in Figs. 3 and 4, respectively. From these two figures, we can conclude that: (1) For a given Q, there is a optimal value of P such that the minimum BER is gained. (2) The increasing the number of pulse shapes is more effective to reduce BER than the increasing the number of pulse positions.

The BER comparisons between the proposed TH/DS system with N-ary BPPM and N-ary BPPM under AWGN channel are shown in Fig. 5. In addition, the simulations of both modulation systems under a realistic UWB multipath channel model, called CM3 channel, are also implemented and presented in Fig. 6. A partial RAKE (PRAKE) receiver with maximum ratio combining (MRC) which combines first 20 resolvable multipaths is employed and the perfect channel estimation is assumed in the PRAKE receiver. Considering the same modulation level and fixed system throughput, the proposed TH/DS N-ary BPPSM system can provide better performance than the TH/DS N-ary BPPM system [12].

V. Conclusions

A TH/DS N-ary BPPSM UWB system was proposed and analyzed in this paper. Based on our derived CHF of the MAI, a simple SER expression of the proposed system under MAI and AWGN has been derived. From the numerical and simulation results, the proposed system is shown to outperform the TH/DS N-ary BPPM system. The analytical SER curves of the proposed system are accurate and verified with the simulations.

References

[1] M. Z. Win and R. A. Scholtz, "Ultra-wide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communications," *IEEE Trans. Commun.*, vol. 48, no. 4, pp. 679-689, April 2000.

[2] M. A. Rahman, S. Sasaki, J. Zhou, and H. Kikuchi, "Error analysis for a hybrid DS/TH impulse radio UWB multiple access system," *in Proc. IEEE International Conference on Ultra-Wideband Systems and Technologies*, pp. 220-224, Sept. 2005.

[3] B. Hu and N. C. Beaulieu, "Accurate performance evaluation of time-hopping and direct-sequence UWB systems in multiuser interference," *IEEE Trans. Commun.*, vol. 53, no. 6, pp. 1053-1062, June 2005.

[4] E. Fishler and H. V. Poor, "On the tradeoff between two types of processing gains," *IEEE Trans. Commun.*, vol. 53, pp. 1744–1753, Sep. 2005.

[5] S. Gezici, et al., "Performance evaluation of impulse radio UWB systems with pulse-based polarity randomization," *IEEE Trans. Signal Processing*, vol. 53, pp. 2537–2549, July. 2005.

[6] S. Gezici, et al., "The tradeoff between processing gains of an impulse radio UWB system in the presence of timing jitter," *IEEE Trans. Commun.*, vol. 55, pp. 1504–1515, Aug. 2007.

[7] F. Ramirez-Mireles, "Performance of ultra wideband SSMA using time hopping and M-ary PPM," *IEEE J. Sel. Areas Commun.*, vol. 19, no. 6, pp. 1186-1196, June 2001.

[8] R. Pasand, S. Khalesehosseini, J. Nielsen, and A. Sesay, "Exact evaluation of M-ary TH-PPM UWB systems on AWGN channels for indoor multiple-access communications," *IEE Proc.-Commun.*, vol. 153, no. 1, pp. 83-92, Feb. 2006.

[9] Qing F. Zhou and Francis C. M. Lau, "Analytical performance of M-ary time-hopping orthogonal PPM UWB systems under multiple access interference," *IEEE Trans. Commun.*, vol. 56, no. 11, pp. 1780-1784, Nov. 2008.

[10] H. Zhang, W. Li, and T. A. Gulliver, "Pulse position amplitude modulation for time-hopping multiple-access UWB communications," *IEEE Trans. Commun.*, vol. 53, no. 8, pp. 1269-1273, Aug. 2005.

[11] H. Zhang, and T. A. Gulliver, "Biorthogonal pulse position modulation for time-hopping multiple access UWB communications," *IEEE Trans. Wireless Commun.*, vol. 4, no. 3, pp. 1154-1162, May 2005.

[12] Y. S. Shen and F. B. Ueng, "An accurate performance analysis of hybrid TH/DS multiple access UWB system using N-ary biorthogonal PPM ," *in Proc. IEEE VTC-Spring*, May 2010.

[13] R. Dilmaghani, M. Ghavami, B. Allen, H. Aghvami, "Novel UWB pulse shaping using prolate spheroidal wave functions," *in Proc. IEEE PIMRC* 2002, pp105-120, Oct. 2002.

[14] L. B. Michael, M. Ghavami, and R. Kohno, "Multiple pulse generator for ultra-wideband communication using hermite polynomial based orthogonal pulses," *in Proc. IEEE Conference on Ultra Wideband Systems and Technologies*, 2002, May, pp. 47-52.

[15] H. Wen and Z. Guoxin, "Orthogonal hermite pulses used for UWB M-ary communication," *in Proc. Internation Conference on Information Technology*, Mar. 2005, pp. 97–101.

[16] N. Boubaker and K. B. Letaief, "Biorthogonal pulse shape modulation for ultra-wideband wireless communication," *in Proc. IEEE GLOBECOM 2004*, Nov. 2004.

[17] S. Majhi, A. S. Madhukumar, A.B. Premkumar, F. Chin, "M-ary signaling for ultra wideband communication systems based on pulse position and orthogonal pulse shape modulation," *in Proc. IEEE WCNC 2007*, pp.2797-2801, Mar. 2007.

[18] J. H. Hwang, S, C. Kim, S. Yoon, B. Kang, and J. S. Park, "Performance analysis of PO-THMA UWB system using mutually orthogonal MHP pulses," *IEEE Trans. Consumer Electronic*s, vol. 53, no. 1, pp. 39-45, Feb. 2007.

[19] John G. Proakis, Digital Communications. New York, NY: McGraw-Hill, 2001.

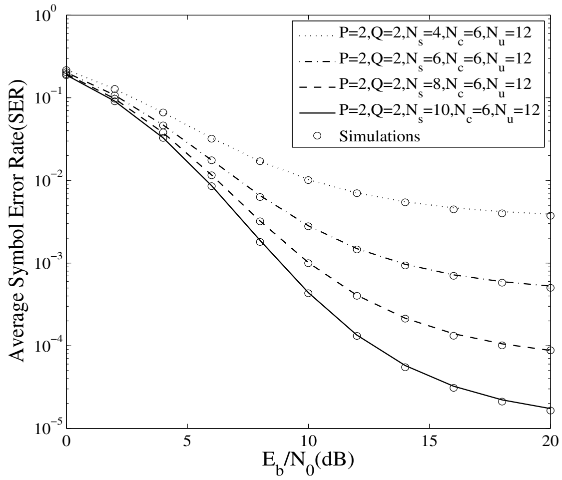

Fig. 1. Average SER of the proposed system for different number of frames $N_s = 6$, 8, 10 and 12. The modulation levels $N = 8$ $(P = 2, Q = 2)$, the number of TH slots $N_c = 6$ and the number of users $N_u = 12$.

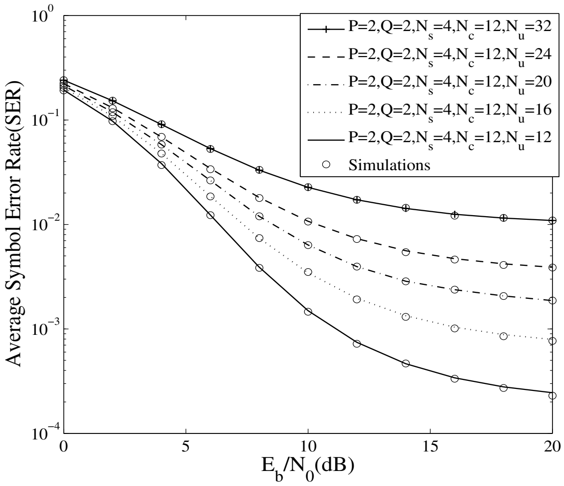

Fig. 2. Average SER of the proposed system for different number of asynchronous users $N_u = 12$, 16, 24 and 32. The modulation levels $N = 8$ $(P = 2, Q = 2)$, the number of frames $N_s = 4$ and the number of TH slots $N_c = 12$.

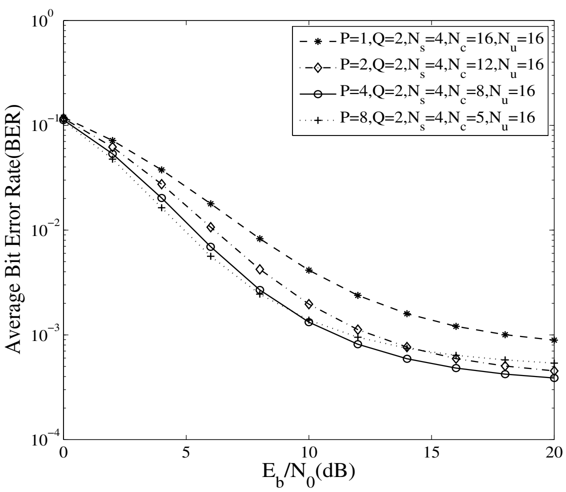

Fig. 3. Average BER of the proposed system for different number of pulse positions $P = 1$, 2, 4 and 8. The number of pulse shapes $Q = 2$, the number of frames $N_s = 4$ and the number of users $N_u = 12$.

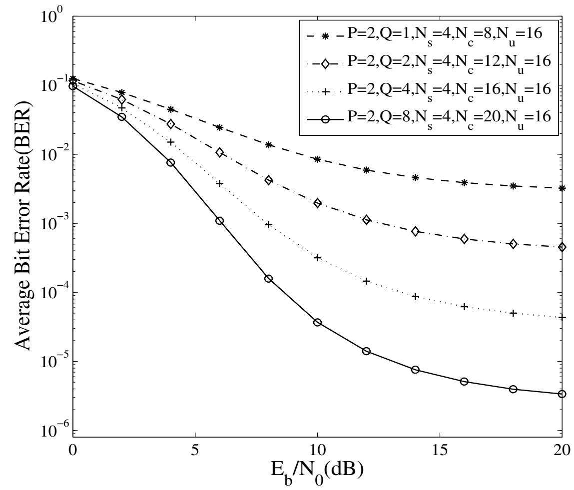

Fig. 4. Average BER of the proposed system for different number of pulse shapes $Q = 1$, 2, 4 and 8. The number of pulse positions $P = 2$, the number of frames $N_s = 4$ and the number of users $N_u = 12$.

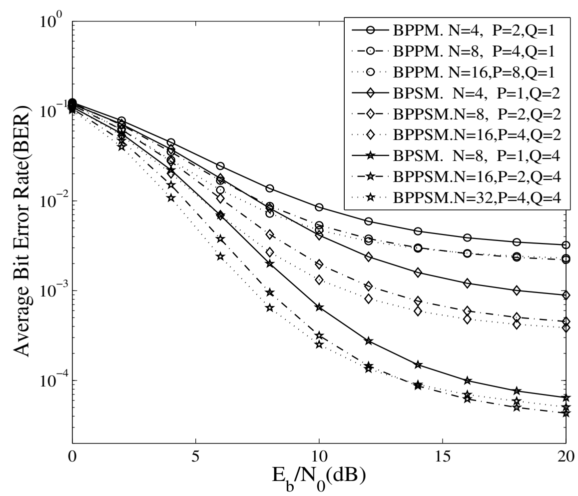

Fig. 5. Performance comparisons of the proposed N-ary BPPSM and N-ary BPPM systems. The fixed ratio $T_b/T_p = 32$, the number of frames $N_s = 4$ and the number of users is 16.

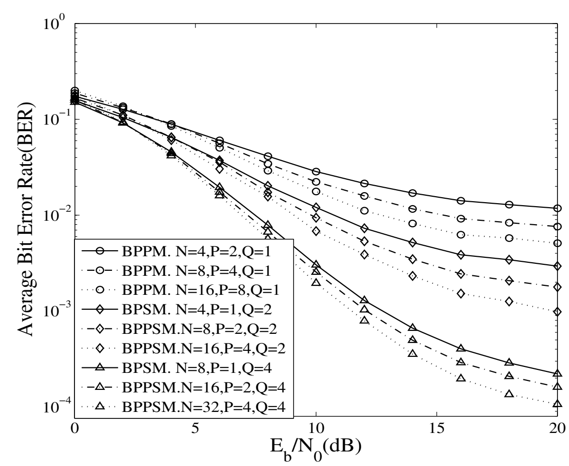

Fig. 6. Performance comparisons of the proposed N-ary BPPSM and N-ary BPPM systems using the partial Rake receivers with 20 fingers in the CM3 UWB fading channel. The fixed ratio $T_b/T_p = 32$, the number of frames $N_s = 4$ and the number of users is 16.