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High Order Template Scheme for Rapid Acquisition in the UWB Communication System

康 秀 藺[*] · 林 小 菊[*] · 이 해 기[**] · 김 성 수[†]
(Gansuren Baasantseren · Xiaoju Lin · Hae-Kee Lee · Sung-Soo Kim)

Abstract – The low power of ultra-wideband (UWB) signal makes the acquisition of UWB signal be a more challenging task. In this paper, we propose the method of high order template signal technique that reduces the synchronization time. Experimental results are presented to show the improvements of performance in the mean acquisition time (MAT) and the probability of detection. The performance compared with the serial search, the truly random search and the random permutation search. It is shown that over typical UWB multipath channels, a random permutation search scheme may yield lower MAT than serial search.

Key Words : Ultra-Wideband, Multipath Channel, Mean Acquisition Time

1. Introduction

The ultra-wide band (UWB) communication systems offer very high data rates by the transmission of pulses with very short duration and low duty cycles where the strict power limitations and the short pulse duration make the performance of UWB systems highly sensitive to timing errors. The time synchronization introduces a major challenge in UWB [1-3]. The synchronization of narrow, low powered UWB pulses has been addressed to some extent by transmitted-reference (TR) modulation.

The acquisition problem has attracted considerable research in the recent works [4], [5]. The acquisition of the UWB signal is a potential bottleneck for system throughput in a packet based network which employs UWB signaling in the physical layer. The problem is mainly due to the following two reasons. Firstly, the received signal power is low, which forces the acquisition system to have a large dwell time in order to improve the signal-to-noise ratio of the decision statistic. Secondly, the large system bandwidth results in very fine time resolution of the ambiguity region, which increases the number of phases in the search space of the acquisition system. Thus, the acquisition system is forced to process the signal over long periods of time before getting reliable estimate of the timing (phase) of the signal. Hence, there is need to develop more efficient acquisition schemes by taking into account the signal and channel characteristics.

The two-stage acquisition technique [6] is used, where the first stage termed coarse acquisition simply finds any of the many multipath components. The second stage, termed fine acquisition, searches for the first arriving path in the reduced uncertainty region [7]. In the proposed implementation, the first stage is a fast version of traditional threshold comparison serial test, called jump-phase search, where the search time is drastically reduced by performing a nonconsecutive search, where the number of cells, noted as H_1, are uniformly spread over the uncertainty region. The second stage takes advantage of a robust noise variance estimate at the first stage to calculate a new, more reliable threshold. Moreover, it exploits the clustered nature of the multipath to better segregate the cells corresponding to incorrect delays, denoted as H_0, from H_1 cells, and detect more reliably the start of the signal, even when the line of sight (LOS) path is severely attenuated.

In this paper, we present the effects of mean acquisition time search space reduction technique with higher order moments and different template signals, which yields to speed up the acquisition process without any additional complexity. We consider the effect of multipath channel on the acquisition performance as appeared in [6]. In this proposed inspection, we also use a different template signal which has more flexibility in dealing with acquisition in multipath channels. Specifically, we divide the search space into some groups and find a set of possible positions of the true phase relative to the positions of the groups. When a set of phases－one from each group is declared to include the

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[*] 정 회 원 : 충북대학교 전기공학부 석사과정
[**] 정 회 원 : 충청대학 전기공학부 교수 · 공박
[†] 교신저자, 정회원 : 충북대학교 전기공학부 교수 · 공박
E-mail : sungkim@chungbuk.ac.kr

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true phase, the second stage tries to find the absolute position of the true phase by searching the relative positions in each group using a different template signal.

The rest of the paper is organized as follows. System model under consideration is described in Section 2. The proposed method of acquisition is discussed in Section 3. Different mean acquisition times discussed in Section 4. Section 5 presents the numerical results and compares the serial search, the truly random search and the random permutation search, and Section 6 concludes the paper.

2. System Modeling

2.1 Signal model

The system modelled as the direct sequence spreading ultra wideband signaling (DS-UWB) with binary phase shift keying modulation (BPSK) is employed [2].The signal pulse shape is the Gaussian second derivative pulse $p(t)$,

$$p(t)=\sqrt{\frac{4}{3\tau_s\sqrt{\pi}}}\left(1-\left(\frac{t}{\tau_s}\right)^2\right)\exp\left(-\frac{1}{2}\left(\frac{t}{\tau_s}\right)^2\right) \qquad (1)$$

The parameter τ_s determines the effective time width of the pulse and consequently the bandwidth. The energy of the pulse $p(t)$ is unity. Then the transmitted signal is given by,

$$s(t)=\sqrt{E_p}\sum_{k=-\infty}^{\infty}b_{\lfloor k/N_d\rfloor}\,\alpha_{[k/N_c]}p(t-kT_f) \qquad (2)$$

where N_d is the number of consecutive monocycles modulated each data symbol b_k, T_f are the pulse repetition period (PRP) where $[.]$, $\lfloor . \rfloor$ denote the integer division remainder and the floor operations respectively. The set $\{\alpha_k\}$ is the direct spreading (DS) code of the length N_c where each takes value +1 or -1. We consider the pulses length N_d as symbol duration and each phase in the acquisition stage is evaluated by correlating N_d pulses, hence the dwell time of the correlation is $T_d=N_dT_f$.

2.2 Channel Model

The UWB channel model proposed by the IEEE 802.15.3a task group is a modified Saleh-Valenzuela model which is fit well for UWB channel measurements [8]. The statistical channel model is given as,

$$h_i(t)=X_i\sum_{l=0}^{L-1}\sum_{k=0}^{K-1}\alpha_{k,l}^i\delta(t-T_l^i-\tau_{k,l}^i) \qquad (3)$$

where $h_i(t)$ is the i^{th} channel realization, $\alpha_{k,l}$ is the multipath channel coefficient, T_l is the delay of the l^{th} cluster, and $\tau_{k,l}$ is the delay of the k^{th} multipath component within the l^{th} cluster. The variable presents the lognormal shadowing effect. For the sake of the notation simplicity, the channel impulse response $h(t)$ can be represented as,

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

where, α_l includes the multipath channel coefficient and shadowing (the pathloss is assumed to be compensated in the link budget), τ_l is the channel sounding sampling time, L is the number of resolvable path. L and α_l can be modified, such that the channel model counts for those paths whose values are less than 10 dB below the maximum peak, or those paths that contain 85% of the total channel's energy [9], [10]. The IEEE 802.15.3a task group suggested an initial set of values for the four different channel environments from CM1 to CM4. In this paper, we just focus on CM1 the line of sight (LOS) scenario for analysis.

In addition, it is usually reasonable to assume that the fading and multipath structure stay essentially constant for at least one signaling interval. It is supposed that the effects of transmit and receive antennas are incorporated into channel effect. For mathematical simplicity, it is also assumed that the symbol time is longer than the channel maximum delay spread. And thus, any inter symbol interference (ISI) effects caused by the multipath channel are ignored. The received signal is then shown as,

$$r(t)=\sqrt{E_p}\sum_{k=-\infty}^{\infty}\sum_{l=0}^{L-1}\alpha_l p(t-kT_f-\tau_l)+n(t) \qquad (5)$$

where $n(t)$ is an additive white Gaussian noise (AWGN) with zero mean and two-sided power spectral density $N_0/2$.

3. Acquisition Algorithm

The serial search technique which has been used in UWB systems [11], [12], [13] typically correlates the received signal with a locally generated template signal, and compares the correlation value with a predefined threshold. The template signal for evaluating the jth phase in the search space is given by,

$$v_j(t)=\sum_{k=0}^{N_d-1}p(t-kT_f-\hat{\tau}_j) \qquad (6)$$

where $\hat{\tau}_j=jt_s$ and $j=0,1,\ldots,N-1$. t_s is the search step size and the number of phases in the search space is $N=T_f/t_s$. If the correlation value exceeds the threshold, the current phase of the template signal is assumed to be the true phase. Otherwise, the phase of the template signal is shifted by the search step size and the correlation is repeated. Usually, a verification stage is employed to confirm the decision made by the acquisition stage. This is performed by J times correlating without shifting the phase of the template signal. If all J correlation values exceed the threshold, the current phase is declared as the true phase. If not, the acquisition stage is resumed and the other phases are evaluated. The probability of false alarm, P_{fa} is defined as the probability that the correlator output exceeds the threshold in a wrong phase (H_0 phase), and J is the penalty time for detecting a false alarm and resuming to the acquisition stage. Probability of detection, P_d is defined as the probability that the correlator output exceeds the threshold in a true phase (H_1 phase).

3.1 The Proposed Method

The search space which includes N phases is divided into G groups. Assume that each group has M consecutive phases and there are D true phases in the search space. We further assume that the D true phases are contiguous and $M \geq D$. We use a special template signal which enables evaluating G phases by each correlation one from each group. The template signal of the first stage is a sum of "G delayed by replicas of the transmitted pulse". The template signal for evaluating the m^{th} phase at the first stage is given by,

$$v_m(t) = \sum_{k=0}^{N_d-1} g(t - kT_f - \hat{\tau}_m) \qquad (7)$$

where $\hat{\tau}_m = mt_s$ and $m = 0, 1, \ldots, M-1$, and $g(t) = \sum_{r=0}^{G-1} p^n(t - rMt_s)$ with n=1, 2, 3, 4 for n^{th} pulse types. If the correlation value in this stage exceeds the threshold, one of the corresponding phases in the G groups is expected to be the true phase. Suppose that at the first stage $\hat{\tau}_m$ is chosen as the true phase, then the second stage searches the G possible positions which are $\{\hat{\tau}_m, \hat{\tau}_m + Mt_s, \hat{\tau}_m + 2Mt_s, \ldots, \hat{\tau}_m + (G-1)Mt_s\}$, with the template defined in (6) with $\hat{\tau}_j = \hat{\tau}_m + jMt_s$ and $j = 0, 1, \ldots, G-1$ to locate the absolute position of the true phase. If none of the hypothesized phases is detected, the first stage is resumed and the search continues.

4. Mean Acquisition Time

4.1 Serial Search

An exact analysis of the proposed method in a noisy channel is too complicated and requires a lot of derivations. Thus, we analyze the proposed method and compare it with the serial search in a noiseless channel and resort to simulation to investigate the performance in a noisy channel. First, consider the simple serial search method with a search space of N phases. The search space can be represented as, $S = \{jt_s : j \in Z \text{ and } 0 \leq j \leq N-1\}$ we assume that there are D contiguous H_1 phases in the search space. With the above assumptions, the mean acquisition time of the serial search is given in [11], [12] by,

$$\overline{T}_{acq(ser)} = \frac{(N-D)^2 + (3N-D)}{2N} T_d \qquad (8)$$

Now, we calculate the mean acquisition time of the proposed method in a noiseless channel, i.e., $P_{fa} = 1$ and $P_d = 1$. Without loss of generality, we assume that the first phase of the true phase set is also the first phase of the search space. Let i be the starting point of a search. Two possible cases must be considered.

First, it is assumed that $D < i \leq M$, i.e., the search process starts from a H_0 phase, and second, $1 < i \leq D$, i.e., the search process starts from a H_1 phase For the first case, the time taken to reach a true phase is,

$$T_{acq(TS)}(i) = (M - i + 1)T_d + T_d + \overline{T}^{(H_1)}_{acq(s2)} \qquad (9)$$

where $\overline{T}^{(H_1)}_{acq(s2)}$ is the mean acquisition time of the second stage after a detection is made at the first stage. Using (8) with N=G, and D=1, $\overline{T}^{(H_1)}_{acq(s2)}$ can be found as,

$$\begin{aligned}\overline{T}^{(H_1)}_{acq(s2)} &= \frac{(G-1)^2 + (3G-1)}{2G} T_d \\ &= \frac{G+1}{2} T_d\end{aligned} \qquad (10)$$

The reason for choosing D=1 is that we assumed that $M \geq D$. Therefore, if detection occurs at the first stage only one of the groups is expected to contain the true phase. Now, suppose that the search process starts from a H_1 phase, i.e., $1 \leq i \leq D$. The acquisition time is then given by,

$$T_{acq(TS)}(i) = T_d + \overline{T}^{(H_1)}_{acq(s2)} = \frac{G+3}{2} T_d \qquad (11)$$

Since the probability of each phase becoming the starting point of the search process is uniform and is equal to $1/M$, the mean acquisition time is given by,

$$\begin{aligned}\overline{T}_{acq(TS)} &= \frac{1}{M}\left[\sum_{i=1}^{D} \frac{G+3}{2} + \sum_{i=D+1}^{M}\left(M - i + 2 + \frac{G+1}{2}\right)\right] T_d \\ &= \frac{(M-D)^2 + GM + 4M - D}{2M} T_d\end{aligned} \qquad (12)$$

4.2 Truly Random Search

The truly random search is one in which the history of previously searched bins are ignored. Thus search variable, $\hat{\tau}_m$ is selected at random from $0 \le i \le M$. Than mean acquisition time computed as,

$$\overline{T}_{acq(truly.rand.ser)} = \sum_{i=1}^{M} \Pr(M=i) = \frac{N}{D} T_d \qquad (13)$$

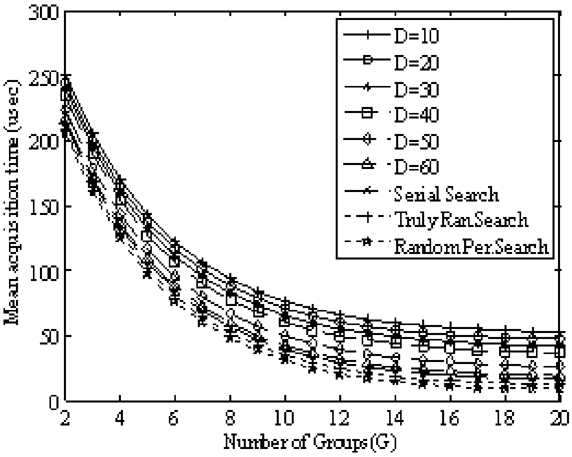

Fig. 1 Mean acquisition time of the serial search, the truly random search, and the random permutation search method at different numbers of groups and different sizes of the true phase set *D*, for *N*=1000.

4.3 Random Permutation Search

The other steps of random permutation search scheme are similar with serial search scheme and truly random search scheme [12], [13]. Random Permutation Search is particular search strategy, the integers $\{0, 1, \ldots, M-1\}$ are randomly permuted and the bins are searched according to this random permutation. More precisely, if σ_m is a random permutation of $0 \le m \le M-1$, then the search random variable is simply $\hat{\tau}_m = \sigma_{j \bmod M}$ for $j = 0, 1, \ldots, M-1$. Than mean acquisition time found to be,

$$\overline{T}_{acq(rand.per.ser)} = \frac{N+1}{D+1} T_d \qquad (14)$$

Figure 1 shows the random permutation search performs better than the serial, the truly random search is only slightly larger than one.

4.4 Probability of detection and false alarm

The probability of false alarm P_{fa} is related to the variance of input noise. Taking into account the input signal noise ratio (SNR) and that the absolute value is used [14],

$$P_{fa} = 2N\left(\frac{T_h}{\sigma}\right) \; with \; N(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{t^2}{2}} dt \qquad (15)$$

P_d is defined as the probability of terminating the search process in a H_1 phase,

$$P_d = Q\left(\frac{A_i}{\sigma}, \frac{T_h}{\sigma}\right) \qquad (16)$$

where A_i is the signal amplitude in the corresponding path and σ is the noise variance. By the same method, the probability of detection P_d can be defined considering the relation of the threshold with the output mean and the relation of the output mean with its standard deviation given by the signal to noise ratio.

5. Numerical Results

In this section, we discuss some numerical results calculated with matlab. In order to evaluate the acquisition performance of the proposed scheme in realistic channels, the channel model [8] CM1 of IEEE802.15.3a is employed in the simulations, which is suitable for typical LOS scenarios with range 0-4m. In the first stage of acquisition, random permutation search scheme is taken into consideration. To avoid inter-symbol interference, the pulse repetition rate T_f is chosen to be 100*ns*. The correlator dwell time T_d is set $N_d T_f$, where N_d the number of consecutive monocycles 10 and search step size is t_s=0.2*ns*. The performance of the proposed UWB acquisition system is method with higher moments and the number of groups. All results for various mean acquisition times are reported in the following graphics. Figure 2 and 3 show the mean acquisition time of the order n^{th} pulse type methods. The results are com-pared with the serial search and the truly random search and

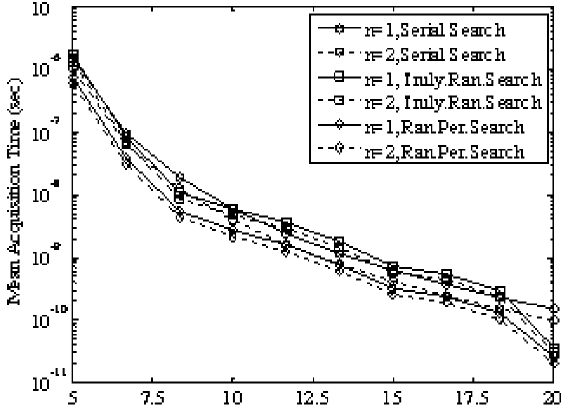

Fig. 2 The mean acquisition time (MAT) are presented for the template signal first and second powers, the serial search, the truly random search, and the random permutation search method.

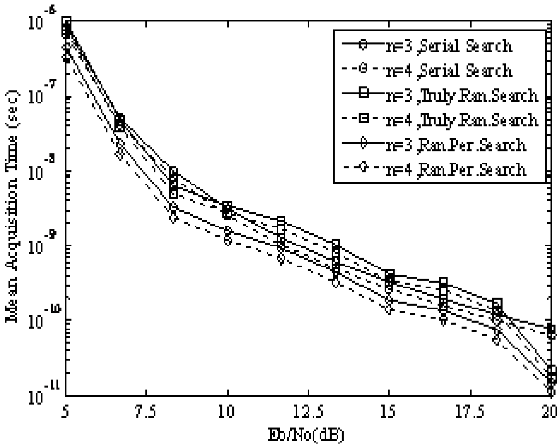

Fig. 3 Different mean acquisition times for the high order n=3, 4 the serial search, the truly random search, and the random permutation search method.

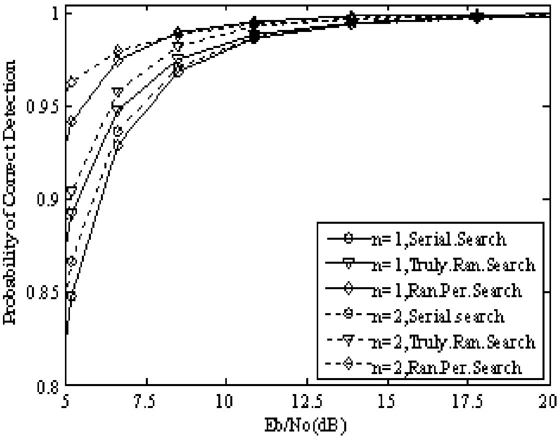

Fig. 4 Probabilities of correct acquisition for the cases where the template signal powers are 1, 2 are presented, comparing with the serial search, the truly random search, the random permutation search method.

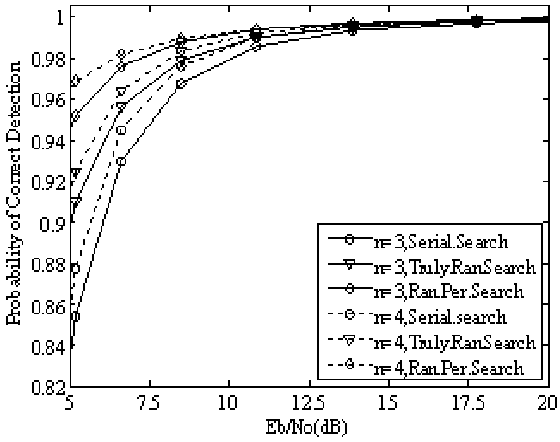

Fig. 5 Probabilities of correct acquisition for n=3, 4 and the serial search are compared with the truly random search, the random permutation search method.

the random permutation search. In this paper we just considered D true phases randomly in the case the truly random search, the random permutation search. The high order template signal with n equal to 3 and 4 mean acquisition time at the random permutation search better than the serial search and truly random search. Figure 4 and 5 show the Probability of Detection for variety the template signal for different signal noise ratio (SNR).The probability of detection performs worse in the case of the serial search with n=1, 2 while the random permutation search with n=3, 4 perform best in the comparison group. Specially, the probability of detection perform well in the random permutation search with order 3 and 4 compared with the serial search and the truly random search.

6. Conclusions

In this paper, we have presented a method of minimizing the mean acquisition time for an UWB impulse radio system by developing high order template signals. While template signal power increases, the mean acquisition time decrease. In the case the random permutation search method performs much better than the serial search and the truly random search. The synchronization is acquired rapidly with low complexity, resulting in preferable performance.

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저자소개

康 秀 蘭 (Gansuren Baasantseren)

2008년 2월 Mongolian Science and Technology University, 전기공학과 (공학사). 2008년 9월~현재 충북대학교 전기공학과 석사과정

<관심분야> Ulltra-wideband Communication system

林 小 菊 (Xiaoju Lin)

2008년 7월 Shenzhen University of China, 전자공학과 (공학사). 2008년 9월~현재 충북대학교 전기공학과 석사과정

<관심분야> LDPC Communication system

이 해 기 (李 海 基)

1981년 충북대학교 공업교육 (공학사). 1985년 성균관대학교 전기공학 (공학석사). 1990년 성균관대학교 전기공학 (공학박사). 1991년~현재 충청대학 전지전자학부 교수

<관심분야> 신호처리, 전력제어, 씨퀀스제어

김 성 수 (金 聖 洙)

1997년 Univ. of Central Florida(공학박사). 1999년 ~ 2001년 우석대학교 전기공학과 조교수. 2001년 9월 ~ 현재 충북대학교 전자정보대학 전기공학부 교수

<관심분야> 디지털통신, 인공지능, 신호처리