A two-stage acquisition scheme based on multiple correlator outputs for UWB signals

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Abstract: In ultra-wideband (UWB) channels, the signal energy in the acquisition receiver spreads over correlator outputs due to rich multipaths, making the output of each correlator have only a small portion of the total energy. To enhance the acquisition performance for UWB signals by exploiting the signals spread over a number of correlator outputs, this paper proposes a two-stage acquisition scheme. In the proposed scheme, decision variables are formed by combining a multiple of correlator outputs, allowing it possible to make use of the signal energy spread over the outputs jointly. Simulation results show that the proposed scheme can provide a gain of about 0.6 dB over the conventional schemes in various UWB channel environments.

Keywords: acquisition, detection, ultra-wideband (UWB)

Classification: Science and engineering for electronics

References


1 Introduction

The ultra-wideband (UWB) techniques, possessing several distinct features characterized by the wide bandwidth, have been adopted in various standards of wireless personal area networks (WPANs) such as IEEE 802.15.3a and 802.15.4a because of their high data rate, high time resolution, and low-power transmission [1].

In UWB systems, the timing information of the received signal must first be acquired prior to data demodulation. Consequently, a rapid acquisition is one of the most important technical issues in UWB systems [2], for which several schemes have been investigated in the literature [3, 4, 5, 6, 7]. In [3], acquisition schemes with various search methods have been proposed with the mean acquisition time derived analytically in a noise-free environment. In [4], a fast acquisition scheme with the permutation search method has been introduced, and [5] has analyzed the schemes in [3] with the tapped-delay-line and IEEE 802.15.3a channel models. A serial search acquisition scheme using specific search spacing based on Fibonacci sequence has been considered in [6]. In [7], randomized search strategies for UWB signal acquisition have been proposed. These conventional schemes, however, employ a single correlator output as the decision variable for detection during acquisition, which inevitably results in performance degradation in UWB channels since the rich multipaths of the UWB channel spread the signal energy for detection over a number of correlator outputs.

The originality of this paper consists in proposing a detection scheme exploiting the signal energy spread over a number of correlator outputs due to rich multipaths effectively. Specifically, this paper proposes a two-stage detection scheme for which, based on a combination of a multiple of correlator outputs, the decision variable is chosen in such a way that the signal energy split by the rich multipaths of UWB channels can be effectively combined. The first stage forms the decision variables by combining multiple correlator outputs and then selects the maximum decision variable. Subsequently, the second stage provides an estimate by choosing the maximum correlator output of the maximum decision variable selected in the first stage. In addition, the information on the optimum number of the correlator outputs to be combined is provided in various UWB channel environments. Simulation results
in various UWB channel environments confirm that the proposed scheme can provide a better detection performance than the conventional schemes employing a single correlator output.

2 Proposed scheme

2.1 System model

Consider a direct sequence (DS)-UWB system [5], where an unmodulated signal (acquisition preamble) is transmitted during the acquisition process. The transmitted DS-UWB signal \( s(t) \) can then be expressed as

\[
s(t) = \sqrt{E_c} \sum_{i=0}^{N-1} c_i p(t - iT_c),
\]

where \( E_c \) is the signal energy; \( c_i \in \{1, -1\} \) is the \( i \)th chip of a pseudo noise (PN) sequence with period \( N \) chips; \( T_c \) is the chip duration; and \( p(t) \) is the second derivative Gaussian pulse [3, 5] with duration \( T_c \). Similarly, the received signal \( r(t) \) can be expressed as

\[
r(t) = \sqrt{E_c} \sum_{i=0}^{N-1} \sum_{j=0}^{L-1} \alpha_j c_i p(t - iT_c - jT_c - \tau T_c) + w(t),
\]

where \( L \) denotes the number of resolvable multipaths; \( \alpha_j \) is the channel coefficient of the \( j \)th multipath; \( \tau \) is the time delay normalized to \( T_c \); and \( w(t) \) is an additive white Gaussian noise process with mean zero and two-sided power spectral density \( \frac{N_0}{T_c} \). The average power of \( \alpha_j \) is \( \frac{1-e^{-\mu}}{1-e^{-\mu L}}e^{-j\mu} \), with \( \mu \) called the decay factor.

In this paper, we consider a parallel acquisition receiver shown in Fig. 1 (a). The receiver first yields the correlator output \( y_m \) by correlating \( r(t) \) with a locally generated template signal \( g_m(t) = \sum_{n=0}^{N-1} c_n p(t - (n + m)T_c) \) over a correlation interval \( NT_c \), where \( m = 0, 1, \ldots, N - 1 \). The absolute value of \( y_m \) is then obtained to remove the influence of the signal conversion due to the channel reflections. Subsequently, the detector produces an estimate \( \hat{\tau} \) of the time delay \( \tau \) based on \( \{|y_m|\}_{m=0}^{N-1} \). The estimate \( \hat{\tau} \) is then checked if it is an element of the hit set \( S_h \) defined as [4]

\[
S_h = \{ \hat{\tau} : P_e(\hat{\tau} - \tau) \leq \lambda_d \},
\]

where \( P_e(\hat{\tau} - \tau) \) denotes the bit error rate (BER) in the subsequent demodulation when the acquired time delay estimate is \( \hat{\tau} \), and \( \lambda_d \) is the desired BER. If \( \hat{\tau} \in S_h \), \( \hat{\tau} \) is transferred to the tracking process; otherwise, the acquisition process resumes.

In the conventional schemes, the detector yields a time delay estimate \( \hat{\tau}_c \) via

\[
\hat{\tau}_c = \arg \max_{0 \leq m \leq N-1} |y_m|
\]

as shown in Fig. 1 (b). In other words, the conventional schemes form the decision variables \( \{z_m\}_{m=0}^{N-1} = \{|y_m|\}_{m=0}^{N-1} \), each based on a single correlator.
output, and produce a time delay estimate from the maximum decision variable. Here, it is noteworthy that, in UWB channels, the signal energy spreads over a number of correlator outputs due to rich multipaths, and therefore, any single correlator output has only a small portion of the signal energy.

**2.2 A two-stage detection scheme**

To effectively exploit the signal energy spread over the multipaths, we now propose a two-stage detection scheme based on a multiple of correlator outputs as shown in Fig. 1 (b).

The first stage forms the decision variables by combining the absolute values of a multiple of consecutive correlator outputs, thus allowing it possible to make use of the signal energy spread over the correlator outputs jointly. It should be noted that the decision variables in the conventional detectors are formed based on a single correlator output, and thus, the signal energy spread over the correlator outputs is individually used for detection.

Denoting the decision variables by \( \{z_m\} \), we then choose the index \( m^\star \) such that

\[
m^\star = \arg \max_{0 \leq m \leq N-1} z_m = \arg \max_{0 \leq m \leq N-1} \sum_{j=0}^{H-1} |y_{m+j}|,
\]

**Fig. 1.** The parallel receiver structure of the conventional and proposed schemes for UWB signal acquisition.
given a predetermined constant $H$, where it is assumed that $y_{N+k} = y_k$ for $k = 0, 1, \cdots, H - 2$. Interestingly, the optimal value of the predetermined constant $H$ remains almost unaffected when the signal-to-noise-ratio (SNR) changes as we shall see in the next section. Finally, the second stage produces an estimate

$$\hat{\tau}_p = \arg \max_{m^* \leq m \leq m^* + H - 1} |y_m|$$

of the time delay. From (5) and (6), it is clear that the conventional schemes are a special case of the proposed scheme with $H = 1$.

In short, while the correlator outputs containing the signal energy split by rich multipaths are individually used in the conventional detectors, the correlator outputs are jointly used in the proposed two-stage detector, and thus, the proposed detector can combine the signal energy split more efficiently, utilizing more accurate information on the signal from more reliable correlator outputs during the detection process.

3 Simulation results

The detection performances of the proposed and conventional schemes are simulated with the IEEE 802.15.3a channel models [8], where four different environments, CM1, CM2, CM3, and CM4, are defined. As the environment changes from CM$k$ to CM$(k + 1)$, the multipaths spread more widely. In this paper, the detection probability is defined as the probability that the estimate $\hat{\tau}$ ($\hat{\tau}_c$ or $\hat{\tau}_p$) is included in the hit set $S_h$.

In the simulations, the period $N$ of the PN sequence, pulse duration $T_c$, and the desired BER $\lambda_d$ are set to 255 chips, 0.4 ns, and $10^{-3}$, respectively. In addition, the demodulation after acquisition is assumed to be performed via binary phase-shift keying and a ten-finger rake receiver with maximal ratio combining.

Fig. 2 shows the detection probabilities of the proposed scheme as a function of $H$ for some SNR values in the IEEE 802.15.3a channel models, where SNR is defined as $E_c/N_0$. As shown in this figure, the detection probabilities in CM1, CM2, CM3, and CM4 are the highest when the values of $H$ are about 10, 11, 12, and 12, respectively, almost regardless of the SNR. We can also see that the detection performance of the proposed scheme becomes worse if the value of $H$ is increased over the optimal value of $H$. This stems from the fact that the increase in the value of $H$ over the optimal value of $H$ can cause more correlator outputs with insignificant signal energy to be included in the combining result.

Fig. 3 compares the detection probabilities of the proposed and conventional schemes, where the optimal values of $H$ obtained from Fig. 2 are used in the proposed scheme. As expected, the proposed scheme exhibits a better detection performance than the conventional schemes. Specifically, the proposed scheme allows a gain of about 0.6 dB over the conventional schemes on the average.
Fig. 2. Detection probabilities of the proposed scheme as a function of $H$ in the IEEE 802.15.3a channel models.

Fig. 3. Detection probabilities of the proposed and conventional schemes in the IEEE 802.15.3a channel models.

4 Conclusion

In this paper, we have addressed a two-stage detection scheme for UWB signal acquisition. To make use of the signal energy spread over a number
of multipaths jointly, decision variables in the proposed scheme are formed by combining a multiple of correlator outputs, among which the maximum is selected in the first stage. The second stage subsequently yields an estimate of the time delay by choosing the maximum correlator output composing the maximum decision variable. From the simulation results, we have observed that the proposed scheme offers a better detection performance than the conventional schemes in various UWB channel environments.

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