Rapid Synchronization for Ultra-Wideband Communication Systems

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Abstract— **Very high data rate packet systems, such as those based on ultra-wideband (UWB) signaling, face an increasingly important challenge – UWB radio uses sub-nanosecond pulses to transmit information, resulting is high resolution in time implying that the acquisition algorithm must employ sub-pulse duration steps, thereby leading to a large search space, which consequently leads to large mean acquisition time (MAT). The role of synchronization is essentially to determine the relative delay of the received signal with respect to a template signal in the receiver. This paper addresses coarse synchronization in UWB multipath environments taking into account the specific properties of UWB signals. Since we are interested in low signal-to-noise ratio environments, the serial search technique is considered and the performance measure is the MAT. This shows how the design of the correlation parameters affects the time to achieve synchronization.**

Index Terms— **Time acquisition, Ultra-wideband, Multipath channel, false alarm and miss Probabilities.**

INTRODUCTION

UWB signaling is being considered for high data rate wireless multimedia applications for the home entertainment and personal computer industry as well as for low data rate sensor networks involving low-power devices. It is also considered a potential candidate for alternate physical layer protocols for the high-rate IEEE 802.15.3 and the low-rate IEEE 802.15.4 wireless personal area network (WPAN) standards [1]. The features of UWB radio which make it an attractive choice are its multiple access capabilities [2], lack of significant multipath fading [3], and ability to support high data rates and low transmitter power, resulting in longer battery life for portable devices. Synchronization produces alignment between transmitter and receiver clocks so that information can be accurately exchanged. Typically, the process of synchronization between the spreading (incoming) pseudo-noise code and the local dispreading (receiver) code is performed in two steps: first, code acquisition, then tracking via one of the available code tracking loops. The focus here is on the first part. In other words, acquisition is a process of successive decisions wherein the ultimate goal is to bring the two codes into coarse time alignment within one code chip interval.

The acquisition problem has attracted considerable research in the recent past [4], [5]. The acquisition of the UWB signal is a potential bottleneck for system throughput in a packet-based network employing 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, increasing 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 a reliable estimate of the timing (phase) of the signal. Hence, there is a need to develop more efficient acquisition schemes by taking into account the signal and channel characteristics.

Since we are mostly interested in low signal-to-noise ratio environments (in the presence of strong interfering signals or deep noise, for example), in this paper, we shall consider serial search techniques [6] exclusively, as opposed to sequential-estimation techniques, the merits of which decrease with decreasing SNR, or any maximum a posteriori probability technique [7], the complexity of which is prohibitive. In this paper, an initial acquisition scheme for impulse based UWB multipath environments is investigated. We study the reduction of acquisition time with minimization of false alarm and miss probabilities by properly adjusting the decision threshold and the number of hypothesized phases.

The rest of the paper is organized as follows: In section I, an introduction is provided; followed by a UWB signal and channel model in section II. Section III presents a UWB acquisition system design. Computational and simulation results are described in section IV. Finally, concluding remarks are summarized in section V.

UWB SIGNAL AND CHANNEL MODEL

a) Signal model

The transmitted UWB signal consists of a train of short pulses, which dithered by a time-hoping (TH) sequence to facilitate multiple accesses and reduce spectral lines. The polarities of the transmitted pulses also can be randomized by using a direct sequence (DS) spreading code to mitigate multiple access interference (MAI). The generalized UWB signal transmitted during the acquisition process for a single user can be expressed as a series of 2^{nd} derivatives of Gaussian pulse [1].

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

The parameter t_n determines the effective time width of the pulse T_p and, hence, it's bandwidth (shown in Figure 1).

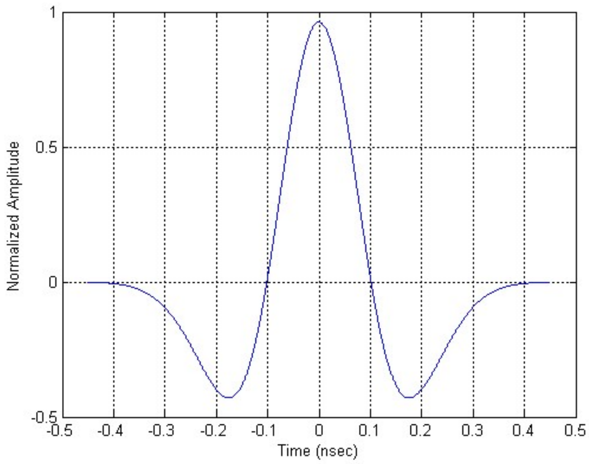

Figure 1: second derivative of Gaussian pulse

Then the transmitted signal is given by

$$x(t)=\sum_{l=-\infty}^{\infty} b_{\lfloor l/N_b \rfloor} a_{[l/N_{ds}]}\psi(t-lT_f-c_{[l/N_{th}]}T_c), \qquad (2)$$

Where N_b is the number of consecutive pulses modulated by each data symbol b_i, T_f is the pulse repetition period (PRP), T_c is the chip duration, which is the unit of additional time shift provided by the TH sequence and $[.]$, $\lfloor . \rfloor$ denote the integer division reminder operation and the floor operation, respectively. The pseudorandom TH sequence $\{c_l\}_{l=0}^{N_{th}-1}$ has length N_{th} where each c_l takes integer values between 0 and $N_{th}-1$, where N_{th} is less than the number of chips per frame $N_f = T_f / T_c$. The DS sequence $\{a_l\}_{l=0}^{N_{ds}-1}$ has length N_{ds} with each a_l taking the value +1 or –1.

UWB systems employ long spreading sequences of a pseudorandom (PN) spanning multiple symbol intervals in order to remove and smoothing spectral lines resulting from the pulse repetition period (PRP) - which makes appear energy spikes in the spectrum- present in the transmitted signal, this problem shown in Figure 2. In the absence of any side information regarding the timing of the received signal, the receiver needs to search through a large number of phases at the acquisition stage, which results in a large acquisition time.

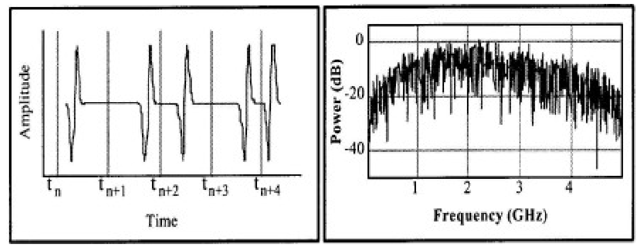

Figure 2: Monocycle dithering and associated spectrum

b) Channel model

The UWB indoor propagation channel can be modeled by a stochastic tapped delay line [8], which can generally be expressed in terms of its impulse response

$$h(t)=\sum_{k=0}^{N_{tap}-1} h_k f_k(t-\tau_k), \qquad (3)$$

Where N_{tap} is the number of taps in the channel response, h_k is the path gain at excess delay τ_k corresponding to the *k*-th path. Due to the frequency sensitivity of the UWB channel, the pulse shapes received at different excess delays are path-dependent [9]. The function $f_k(t)$ models the combined effects of transmitting and receiving antennas and propagation channel corresponding to the *k*-th path of the transmitted pulse.

The received signal from a single user can then expressed as

$$r(t)=\sum_{l=-\infty}^{\infty} b_{\lfloor l/N_b \rfloor} a_{[l/N_{ds}]} w_r(t-lT_f-c_{[l/N_{th}]}T_c-t_d)+n(t) \qquad (4)$$

where

$$w_r(t)=\sum_{k=0}^{N_{tap}-1} h_k \psi_k(t-\tau_d), \qquad (5)$$

is the received waveform corresponding to a single pulse. Here $\psi_k(t)=f_k(t)*\psi(t)$ is the received UWB pulse from the *k*-th path. The duration of the received pulse T_w is assumed to be less than the chip duration T_c. The propagation delay is denoted by t_d and $n(t)$ is a zero mean noise process. Given the received signal, the acquisition system attempts to retrieve the timing offset t_d .

UWB TIME ACQUISITION

a) False Alarm and Miss Probabilities

The presence of noise causes misses and false alarms in the code acquisition process. The false alarm and miss probabilities are the major design parameters of an acquisition technique. The false alarm probability P_{FA} , which occur when a false detection in the noise only (related to the variance of the input noise) portion of the signal is regarded as that of a direct path signal. The miss probability P_M occurs when the actual direct path signal is lost and a multipath signal is falsely declared to be direct path signal.
If the signal is transmitted through the multipath channel, as described in previous section, the received signal *r(t)* can be represented from (4) and (5) by

$$r(t) = \alpha x(t-\tau_d) + \sum_{k=1}^{L_p} \alpha_k s(t-\tau_k) + n(t) \qquad t \le \frac{T_p}{2} \tag{6}$$

where $\tau_d < \tau_1 < \tau_2 < ... < \tau_{L_p}$. The parameter τ_k and α_k are those of the k-th reflected signal component. The number of multipath signals L_p is unknown a priori. $x(t)$ has been truncated to $T_p/2$, which it is the observation of the signal prior to and including the arrival of the strongest path. Let τ_{peak} and α_{peak} be the arrival time and amplitude of the shortest path, which have been determined by correlation in the receiver, and normalize and shift the received signal as

$$\begin{aligned} \delta_d &= \tau_{peak} - \tau_d & \delta \ge 0 \\ \rho_d &= \alpha_d / |\alpha_{peak}| & -1 \le \rho_d \le 1 \end{aligned} \tag{7}$$

The duration of the search region for the time δ of arrival of the direct path signal is limited to prevent the probability of false alarm P_{FA} from becoming too large. Defining θ_δ is as a limiting threshold on δ so that the direct path signal is searched over the portion of the received signal $x(t)$ satisfying $t \ge -\theta_\delta$. Then the iterative search process stops when no more paths satisfying $\rho \ge \theta_\rho$ are detected in the search region, where θ_ρ is the normalized detection threshold of ρ .
The probability of missed P_M can be evaluated as:

$$\begin{aligned} P_M &= pr(\delta > \theta_\delta \quad or \quad \rho < \theta_\rho) \\ &= 1 - \Pr(0 \le \delta \le \theta_\delta \; and \; \theta_\rho \le \rho \le 1) \\ &= 1 - P_0 - (1-P_0)\int_{\theta_\rho}^{1}\int_{0}^{\theta_\delta} f_{\delta\rho}(\delta,\rho \mid \delta \ne 0)\, d\delta d\rho. \end{aligned} \tag{8}$$

where P_0 is the probability that the direct signal is the strongest signal, where $P_0 = \Pr(\delta = 0) = \Pr(\rho = 1)$ and $P_{DET} = 1 - P_M$ give the probability of detection.
Probability of false alarm P_{FA} can be evaluated as:

$$\begin{aligned} P_{FA} = &\int_0^{\theta_\delta} (1 - e^{-(\theta_\delta - \delta - T_p + B\gamma)/C}) f_\delta(\delta \mid \delta \ne 0)\, d\delta . (1-P_0) \\ &+ (1 - e^{-(\theta_\delta - \delta - T_p + B\gamma)/C}) P_{0.} \end{aligned} \tag{9}$$

Where the constants B and C depend on the structure of the signal template $s(t)$, the signal model for 2^{nd} derivative of Gaussian with pulse repetition $T_p = 312.5\,ns$, and $\gamma = \theta_\rho . \sqrt{SNR}$.

b) Mean Acquisition Time

Let us assume that we cycle through and test a total of N different hypothesized phases in each search cycle until the correct phase is detected. We associate a penalty time of T_{fa} seconds $T_{fa} >> T_d$ with a false alarm. The penalty time associated with a miss is NT_d , where T_d is the dwell time. If the correct phase is in the n-th hypothesized position, and there are j misses and k false alarms, the overall acquisition time is given by

$$T_{acq}(n,j,k) = nT_d + jNT_d + kT_{fa} \tag{10}$$

Hence, the mean overall acquisition time is

$$\overline{T}_{acq} = \sum_{n=1}^{N}\sum_{j=0}^{\infty}\sum_{k=0}^{K} T_{acq}(n,j,k) P(n,j,k), \tag{11}$$

Where

$$P(n,j,k) = P(k \mid n,j) P(j \mid n) P(n) \tag{12}$$

As a result

$$\overline{T}_{acq} = \sum_{n=1}^{N}\sum_{j=0}^{\infty} \frac{1}{N}(1-P_{DET})^j P_{DET} \, . \sum_{k=0}^{K} P_{FA}^k (1-P_{FA})^{K-k} (nT_d + jNT_d + kT_{fa}) \tag{13}$$

SIMULATION RESULTS

The performance of the proposed UWB acquisition system was evaluated through the calculation of the mean acquisition time of the overall system. The following values for the system parameters were chosen for the calculations. The TH sequence period $N_{th} = 128$, the chip duration was chosen to be $T_c = 10\,ns$, the dwell time was $T_d = 5\,ns$, the number of hypothesized search cells was 64, 128, 256 cells. The time delay threshold for probability false alarm and detection was θ_δ= 100ns, $p(t)$ was selected as the 2^{nd} derivative of a Gaussian function with which has a pulse width $T_w = 3.562\,ns$, and PRP was $T_p = 312.5\,ns$, under the restricted average transmit power limitations on UWB transmissions resulting from the part 15 limits imposed by the FCC [2]. The frame duration was chosen to be $T_f = 100\,ns$.

Figure 3 shows the affects of pulse width in mean acquisition time with different values of SNR.

Figure 4 gives the mean acquisition time versus signal-to-noise ratio with different values for number of hypothesized phases, which shows the large number of hypothesized phases the large of mean acquisition time.

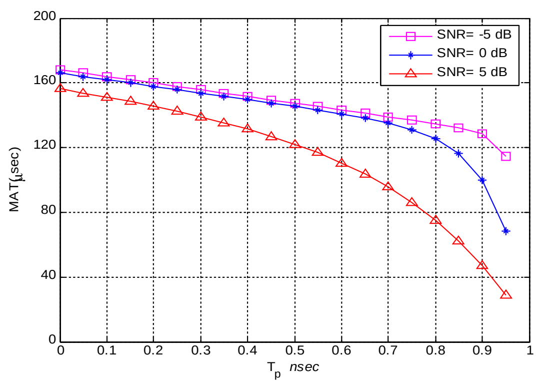

Figure 3: The mean acquisition time versus pulse waveform width, with three different SNR {-5, 0, 5}dB.

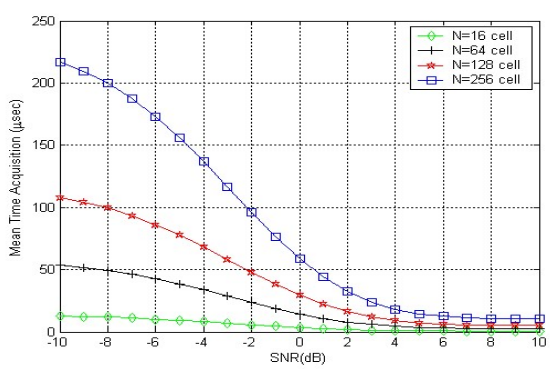

Figure 4: Mean acquisition time for different number of hypothesized search cells, $\theta_\rho = 0.75$.

The normalized threshold, θ_ρ, sets the detection and false alarm probabilities, as well as the mean acquisition time. For Figure 5 shown below, normalized thresholds of θ_ρ= 0.25, 0.50, and 0.75 are assumed.

The differences in the two graphs (Figure 4 & 5) show the acquisition performance as a function of detection and false alarm penalty time (with different parameters for the receiver design). As the signal-to-noise ratio increases the numbers of detections increase and false alarms decrease, both graphs converge to the same mean acquisition time.

Figure 6 shows, receiver detector probability signal detection P_{DET} versus E_B/N_0 for various thresholds (0.25, 0.50, 0.75). The detection probability had worse performance when large thresholds were used with fixed signal-to-noise ratio.

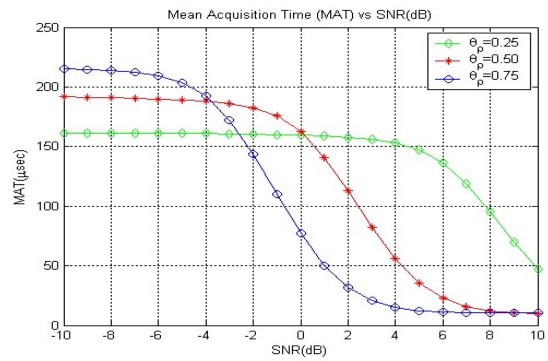

Figure 5: Mean acquisition time for different normalized signal strength threshold values.

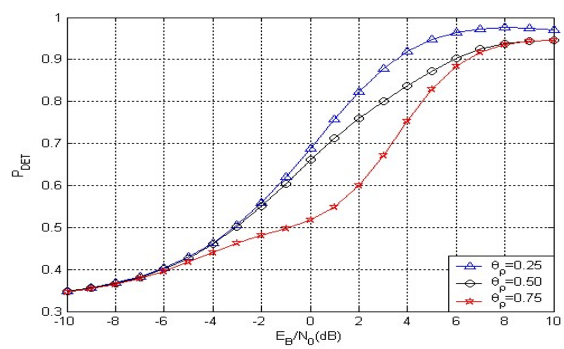

Figure 6: detection probability as a function of E_B/N_0 (dB) for the receiver acquisition stage, the normalized threshold θ_ρ was varied.

The curves in Figure 7 indicate the tradeoff between false alarm probability versus detection probability for different values of SNR's. Better performance of detection probability can be obtained with more concave curves. At lower signal-to-noise ratios, the acquisition time is dominated by the probability of false alarms P_{FA}, which depends on code length and false alarm penalty time.

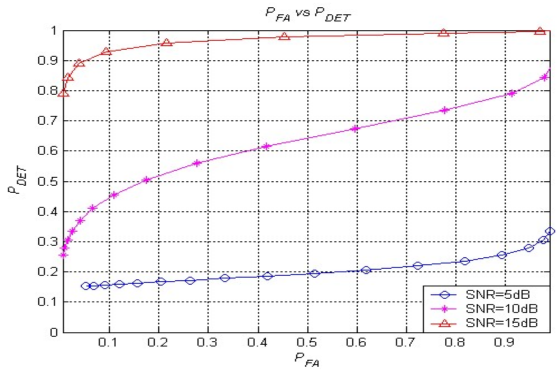

Figure 7: False alarm probability P_{FA} versus detection probability P_{DET} for different SNR's.

CONCLUSIONS

Synchronization of a signal is a first step is performing the correct demodulation of the data it contains. In UWB, bandwidths are over 1 GHz, and the synchronization process has an important impact on the overhead needed for each data packet compared to the amount of information. In this paper we have presented a coarse acquisition part suitable for UWB impulse radio, in the presence of multipath environments. The study relied upon a reduced search approach in order to investigate initial synchronization design parameters. Optimal thresholds that lead to minimum mean acquisition time with all signal-to-noise ratios were used for comparison purposes.

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