SIGNIFICANCE OF STEP SIZE IN THE ACQUISITION PERFORMANCE OF COHERENT IR-UWB RECEIVERS

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ABSTRACT

The sparsely pulsed ultra-wideband (UWB) waveform has to be detected using efficient search strategies. Consecutive serial search (CSS) and permuted search strategies have been used for pulse detection. CSS results in a large average acquisition time when low duty cycle pulses are used. Permuted search strategies circumvent this problem by exploiting the dense multipath characteristic of the UWB signal. A host of parameters influence the acquisition performance in the case of CSS and permuted search strategies. This paper discusses the significance of step size in the acquisition performance of coherent impulse radio ultra-wideband (IR-UWB) receivers. Using theoretical analysis and simulations, it is established that for channel models with different multipath spreads, the step size minimally affects the acquisition performance of a single pulse correlator in the case of permuted search strategies. For CSS, the acquisition performance changes with step size.

Index Terms— Ultra-Wideband Communications (UWB), Synchronization

1. INTRODUCTION

Impulse Radio ultra-wideband communications is carried out using sparse sub-nanosecond pulses. The impulse radio UWB waveform has a duty cycle as low as 1%. Typically, an IR-UWB waveform comprises of multiple frames that make up a symbol. A bit is transmitted in one symbol duration for binary signaling schemes.

The problem of detection involves locating sparse pulses of the UWB waveform. The need to accurately locate these pulses necessitates the development of fast synchronization algorithms. Since the width of the UWB pulse is of the order of nanoseconds and the signal has a low duty cycle, traditional narrow band approaches like early-late gate synchronization are difficult to extend to UWB systems.

Synchronization techniques like CSS, totally random search, bit reversal search, look-and-jump-by-K-bins have been proposed in [1] [2]. Bit reversal search and look-and-jump-by-K-bins have a permuted search order and are usually classified as permuted search strategies. As the multipath components are often clustered in a small portion of the frame and not uniformly distributed in the frame, the CSS cannot achieve the same performance as that of the permuted search strategies. Performance comparisons of these schemes under AWGN and fading channels have also been carried out [3]. Our objective in this paper is to characterize the effect of step size on the acquisition performance of the single pulse correlator IR-UWB receiver. Step size is an important parameter of interest in narrowband systems and can affect acquisition performance. Since the number of bins per frame is inversely proportional to the step size, variations in the step size can potentially affect the acquisition performance of the IR-UWB receivers. Due to the differences in the search methodology of CSS and permuted search strategies, the acquisition performance is affected differently. This paper will show that the dependence of acquisition performance on step size is more pronounced for the CSS compared to permuted search strategies.

In section 2, the system, channel models and the detection scheme have been discussed. Section 3 describes the method of pulse acquisition and computes the expressions for the Average Acquisition Time (AAT) and False Alarm Rate (FAR). The simulation results are provided in section 4 followed by conclusions and references in sections 5 and 6.

2. SYSTEM MODEL

The system is data-aided and there is no pseudo random time hopping of the pulse during the training phase. Binary pulse amplitude modulation (BPAM) is adopted. The signal transmitted is as follows:

$$s(t) = \sum_{j=0}^{\infty} L_{\lfloor j/N_f \rfloor} \sqrt{E_p}\, p(t - jT_f), \qquad (1)$$

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where, $L_{\lfloor j/N_f \rfloor} = \pm 1$ is the bit sequence. As the algorithm is concerned with initial pulse acquisition, $L_{\lfloor j/N_f \rfloor}$ is set to all 1's. The frame duration is assumed to be much greater than the pulse duration ($T_f \gg T_p$). E_p is the pulse energy and $p(t)$ is the second derivative normalized Gaussian pulse [1].

A detailed description of the UWB channel model can be found in [4] where curve fitting is done on empirical data for various indoor environments. The overall power profile of the channel decays exponentially and each fading statistic is log-normally distributed. In this paper, a tapped delay line channel model is used to represent the channel by considering only the resolvable multipath components.

$$h(t) = \sum_{l=0}^{N_m - 1} \alpha_l \delta(t - \tau_l), \tag{2}$$

where there are N_m resolvable multipath components with delay τ_l corresponding to the l^{th} multipath component. α_l is the channel coefficient and is log-normally distributed. The received signal is:

$$r(t) = \sum_{j=0}^{\infty} \sqrt{E_p} g(t - jT_f - \tau_0) + n(t), \tag{3}$$

where, $g(t) := p(t) * h(t + \tau_0)$ spanning $[0, T_m]$, and T_m is the multipath spread of the pulse.

No inter-frame interference is assumed. This is a reasonable assumption as the multipath delay spread is typically a small fraction of the frame duration.

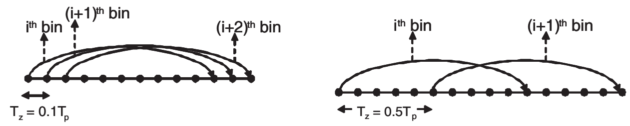
2.1. Detection for Coherent Receivers

Resolvable multipath components are available at the receiver end as the delay spread is greater than a single pulse duration. Provided accurate synchronization and complete channel state information (CSI) are available, the multipath energy can be combined to improve the SNR and consequently the performance of the system. However, the multipath arrivals of a single UWB pulse are unknown at the initial stage of acquisition. This precludes the option of performing correlation with a template signal that is constituted by multiple copies of the pulse shaping waveform spaced out in time corresponding to the discrete multipath arrivals. Therefore, correlation is performed using a single pulse correlator. This paper deals solely with locating any one of the resolvable multipath components. It characterizes the dependence of the step size on the acquisition performance of receivers that use permuted search strategies and compares the results with that of CSS.

After one resolvable multipath is located, a serial search can be performed the region of search can be restricted to the multipath spread to locate the other components.

2.2. Step Size of the Single Pulse Correlator

Each frame is divided into N bins of identical length that equals the pulse duration T_p. The bins are further classified as valid and null depending on whether they contain a pulse or not. These bins are setup in a frame based on the step size. Step size is the separation in time from the start of the previous bin to the start of the next. It is expressed as a fraction or multiple of the pulse duration T_p. The way the bins are setup is shown for two different step sizes in Fig. 1.



(a) Step size $= 0.1T_p$ (b) Step size $= 0.5T_p$

Fig. 1. Different step sizes.

The CSS takes longer to acquire the pulse since the total number of bins increase as the step size gets smaller. Bins are scanned consecutively to obtain the decision statistic and this increases the time taken to detect the UWB pulse. This results in an increased AAT.

For permuted search strategies, the acquisition performance mainly depends on the ratio of the valid bins to the total number of bins and not the step size. The ratio is about the same for different step sizes for a channel model.

3. TOTALLY RANDOM AND PERMUTED SEARCH STRATEGIES

Totally random search strategy selects bins with uniform probability at any given time instant. This allows for selection of a particular bin multiple times as opposed to a permuted search strategy where all bins are exhausted without scope for repeated selection of a particular bin during acquisition. However, this incongruity does not translate into a large loss in performance. The totally random search strategy simplifies the Markov chain model, analysis and has been used as a lower bound for the performance of permuted search strategies.

A bin is picked at random from a frame. The bin which has the same width as the pulse is correlated with the single pulse correlator. The correlator output at a bin of interest at the j^{th} received frame is given by,

$$U_j = \sqrt{E_p} R_{gp}(\tau_l - \tau_0 - jT_f) + \eta_p, \tag{4}$$

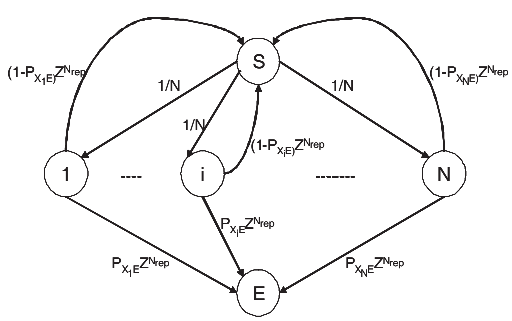
where, $R_{gp}(\tau_l) := \int_{-\infty}^{\infty} g(t)p(t-\tau_l)dt$, $\eta_p := \int_{-\infty}^{\infty} n(t)p(t-\tau_l)dt$, η_p is Gaussian distributed with zero mean and variance $N_0/2$. $E_u := \sqrt{E_p} R_{gp}(\tau_l - \tau_0 - jT_f)$ is the mean. U_j is a Gaussian random variable with zero mean or non-zero mean depending on whether the bin is null or valid.

The squared correlator output is used as the decision statistic to overcome sign ambiguity. The decision statistic is compared with a threshold Γ. If it is under the threshold, the algorithm returns to the starting position. If it exceeds the threshold, the algorithm moves to the absorption state. Repetitions can be used in pulse acquisition to keep the FAR below an acceptable level. Repetitions is the process of averaging the squared correlator output of a particular bin across different frames to get a decision statistic. This averaging reduces the probability of a pulse being declared incorrectly. The decision statistic is given by,

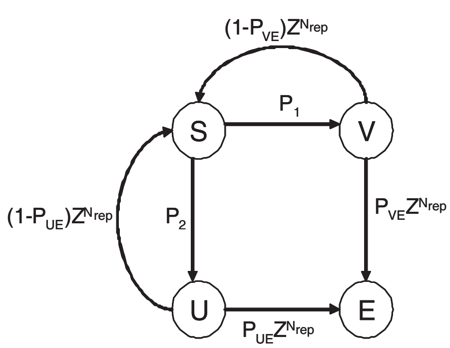
$$\overline{U_{ds}^2} := \frac{1}{N_{rep}} \sum_{j=k}^{k+N_{rep}-1} U_j^2, \tag{5}$$

where, $\overline{U_{ds}^2}$ is χ^2 distributed with a non-centrality parameter that is given by $\lambda = E_u^2$. The number of degrees of freedom of the χ^2 random variable equals the number of repetitions and is denoted by N_{rep}. Performing repetitions helps improve the SNR and consequently, the performance of the system. The AAT is minimized by picking the repetitions times properly [5].

The steps for pulse acquisition using the totally random search strategy are as follows:
Step 1: From the incoming frame, pick a bin at random
Step 2: Perform repetitions to obtain a decision statistic shown in (5) from the correlator outputs shown in (4)
Step 3: If (decision statistic $\leq$ threshold), goto Step 1, Else goto Step 4
Step 4: End



(a) Markov chain model



(b) Reduced signal flow graph

Fig. 2. Signal flow graphs

The Markov chain model for the totally random search strategy is shown in Fig. 2(a), where Z is the unit delay operator. The model has $(N+2)$ states where $1, 2, ...N$ correspond to the bins in a frame, S is the starting state and E is the absorption/end state. An equivalent reduced signal flow graph as shown in Fig. 2(b) is used to simplify the analysis. The valid (V) and the null (U) bins are grouped together to develop the reduced signal flow graph. A verification stage can also be added to this model to further reduce FAR and achieve an AAT comparable to the one obtained using the current algorithm [5].

As all bins are equally likely to be picked, $P_1 = N_v/N$ and $P_2 = N_u/N$ where N_v, N_u are the number of valid and null bins respectively in the frame of interest. The transition probability,

$$P_{X_iE} = P(\overline{U_{ds}^2} > \Gamma), \tag{6}$$

where, Γ is the detection threshold. The transition probabilities P_{VE} and P_{UE} can be computed easily as states X_1 to X_N have the same steady state probability.

$$P_{VE} = \frac{1}{N_v} \sum_{i \epsilon V} P_{X_iE}, P_{UE} = \frac{1}{N_u} \sum_{i \epsilon U} P_{X_iE} \tag{7}$$

$P_{VS} = (1 - P_{VE}), P_{US} = (1 - P_{UE})$ are the other transition probabilities in the reduced signal flow graph. The expressions for the AAT and FAR are found [6] to be:

$$\overline{T} = \frac{N_{rep}(P_1 P_{VE} + P_2 P_{UE})}{\left[1 - (P_1 P_{VS} + P_2 P_{US})\right]^2} \tag{8}$$

$$FAR = \frac{P_2 P_{UE}}{P_1 P_{VE} + P_2 P_{UE}} \tag{9}$$

From the theoretical expressions, it is observed that the AAT and FAR depend on the aforementioned transition probabilities which vary with every bin. This makes it difficult to formulate the dependence of AAT and FAR on the step size in closed form. Also, parameters can be set to minimize the AAT for a fixed FAR.

4. SIMULATION RESULTS

A second derivative normalized Gaussian pulse is used for correlation [1]. Pulse duration $T_p = 0.7ns$ and frame duration $T_f = 100ns$. The step size is denoted by T_z and the number of bins in the frame is $N = T_f/T_z$. Since the algorithm operates over frames, $SNR = E_p/N_0$. The threshold $\Gamma = 0.05E_p$ in our simulations. The AAT will be expressed as a multiple of frame duration T_f. Simulations were performed for tapped delay line channel models with varying multipath spread. Results shown in Fig. 3 are based on a tapped delay line channel model with 9 resolvable taps spaced by T_p.

As we can see from Fig. 3, the curves for totally random search overlap while the curves for CSS change with step size.

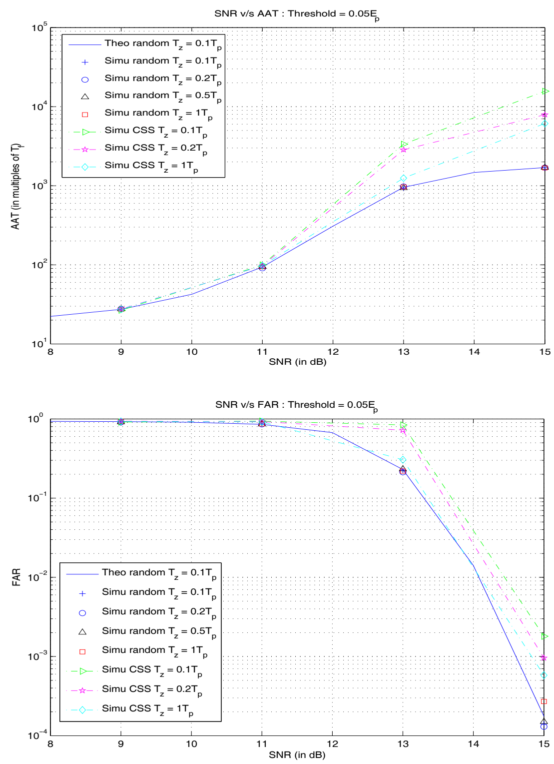


Fig. 3. Performance curves for different step sizes

This means that the acquisition performance of the coherent IR-UWB receiver that uses totally random search strategy is not strongly influenced. From simulations, we have found that the performance of permuted search strategy mainly depends on the ratio of the valid bins to the total number of bins. Although the step size changes, the ratio remains unchanged. This leads to an unchanged AAT and FAR.

It is observed that the performance of CSS improves as the step size increases. The CSS with a larger step size can be perceived as the look-and-jump-by-K-bins search strategy [1]. The performance of the look-and-jump-by-K-bins is better than that of totally random search and bit reversal search [5]. However, when the step size is small, the acquisition performance is poor compared to other permuted search strategies.

Notice that in Fig. 3, the AAT increases with increasing SNR. On the other hand, the FAR decreases with increasing SNR. If the FAR is fixed at a particular level, the AAT will decrease with increase in SNR as shown in Fig. 4. This agrees with intuition because the acquisition performance gets better with increasing SNR.

5. CONCLUSIONS

From a cluster of noisy UWB pulses contained in a frame, any one pulse needs to be located. Totally random search

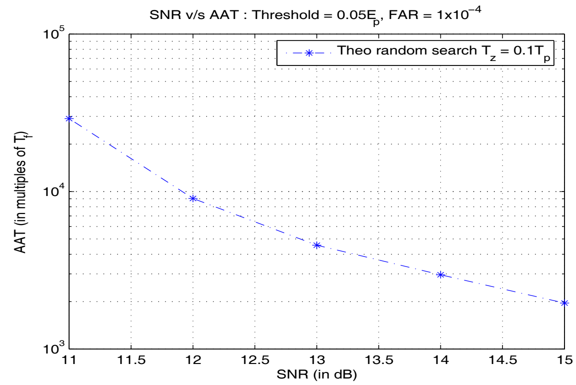


Fig. 4. SNR v/s AAT : Fixed FAR $= 10^{-4}$ (Theory)

strategy has been used as a model for permuted search strategies to perform theoretical analysis and simulations to locate the pulse in an indoor environment. It has been established that the step size does not strongly influence the acquisition performance of the single pulse correlator IR-UWB receiver when permuted search strategies are used to locate the pulse. This is because the acquisition performance of the IR-UWB receiver is dependent on the ratio of the valid bins to the total number of bins. Further, the stronger dependence of acquisition performance on the step size for the CSS has been brought to the fore.

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