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March 21, 2005

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Abstract [1]—**Transmitted–reference (TR) receivers avoid the stringent synchronization requirements that exist in conventional pulse detection schemes. However, the performance of such receivers is highly sensitive to precise timing acquisition and tracking as well as the length of their integration window. This window in TR receivers defines the limits of the finite integrator prior to the final decision making block. In this paper, we propose a novel technique that allows us to extract the timing information of the integration window very accurately in UWB-TR receivers in the presence of channel noise. The principles of the method are presented and the BER performance of a modified UWB-TR receiver is investigated by computer simulation. Our studies show that the proposed estimation technique adds value to the conventional TR receiver structure with modest increase in compleaxity.**

Keywords: Transmitted-reference (TR), ultra-wideband (UWB), timing jitter, interference mitigation, synchronization, acquisition, tracking.

I. INTRODUCTION

The challenge posed by synchronization of narrow, low powered UWB pulses has been addressed to some extent by transmitted-reference (TR) modulation. TR receivers [1] avoid the stringent synchronization requirements that exist in conventional pulse detection techniques by eliminating the need for individual pulse synchronization with locally generated templates. This means that the sampling in TR receivers is performed after correlating the received signal with its delayed replica, thus the sampling requirements are relaxed to the baseband signals. As a result, the need for synchronization of the received short duration RF pulses and very fast and expensive ADCs are eliminated.

Although TR receivers ease the strict synchronization requirement in UWB systems, their performance is largely dependent on the appropriate use of their integration window in the presence of channel noise. Fig. 1 identifies the integration window in TR receivers.
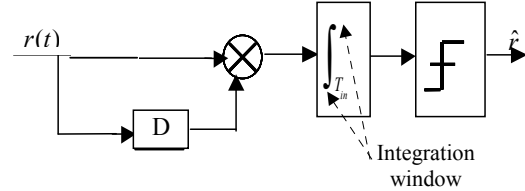

Figure 1: Representation of integration window in TR receivers

The integration window introduces two important design parameters; *length* of integration interval and *accurate position* of the integration interval. The length of integration window plays a major role in the performance of UWB-TR receivers in both LOS and NLOS channels. Fig. 2 illustrates an example of the importance of integration window length in UWB-TR receivers.
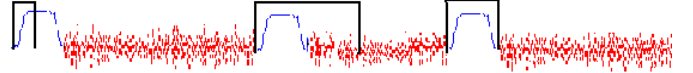

Figure 2: Example of an UWB signal and variations of the integration window length in TR receivers

As shown in the above illustration, the first window from left is too narrow to capture the total signal energy, while the window in the middle is too wide and introduces more noise in to the system. Finally, the window in the right provides the proper length to capture the signal energy without introducing additional noise. Optimal length for integration window in multipath channels is studied in [8-9]. In those papers, Mitra, and Franz propose two methods to estimate the length of the integration window in indoor channels. The first approach is based on a generalized likelihood hypothesis test for estimating the delay spread in the channel. However, this technique always results in estimating the length of the integration window by finding the maximum allowable delay spread. The second approach proposed by Mitra and Franz is to define the integration window length based on formulating a hypothesis testing problem for maximizing the effective SNR. The second method offers strong performance gains over the first approach, which simply uses the maximum allowable delay spread [9].

The accurate timing acquisition and tracking of integration window for each received bit is another important factor in the performance of UWB-TR receivers that has not been explored yet. Any deviation from the precise position of the integration window causes a decrease in SNR of the received signal and results in false alarm and severe performance degradation of the receiver. Fig. 3 represents an example of the importance of the integration window's position in UWB-TR receivers.
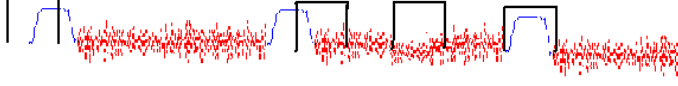

Figure 3: Example of an UWB signal and variations of the integration window's position in TR receivers

As shown in Fig. 3, although the proper length for integration window from the previous example (Fig. 2) is employed, the receiver can still suffer from significant performance degradation due to improper position of the integration window. In TR receivers, if the position of the integration window is detected based on the traditional energy detection techniques, the noise-on-noise interference between the reference and data pulses can produce false detection of the integration window in the presence of channel noise or intentional jamming. Also the exhaustive searched based sliding correlators can take a very long time to converge and add to the complexity of the receiver. Therefore, precise acquisition and tracking of the integration window in noisy channels is the key requirement to successful operation of UWB-TR receivers. In this paper, we introduce a simple and novel method to accurately estimate the integration window in conventional TR receivers. The organization of this paper is as follows. Section II discusses the integration window estimation strategy. Section III presents the performance analysis of the proposed estimation method. Concluding remarks are summarized in Section IV.

II. INTEGRATION WINDOW ESTIMATION STRATEGY

The integration window estimation strategy that we introduce in this paper is based on introducing two additional tasks called SNR Enhancing and Acquisition/Tracking to conventional TR receiver structure. Fig. 4 represents the block diagram of a modified TR receiver with integration window estimation capability.
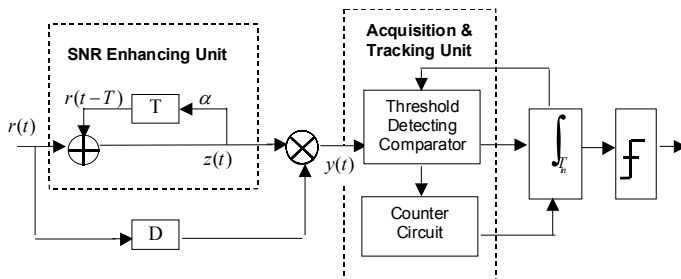
The SNR enhancing unit provides interference suppression to TR receivers and improves the SNR of the reference pulses for initial acquisition of the integration window. Once the SNR is enhanced, the strong signal, $z(t)$, will be multiplied with a delayed replica of the received signal, $r(t)$, as

$$y(t) = r(t - D).z(t) \qquad (1)$$

At this point the acquisition and tracking unit estimates the start and end of the integration window, T_{in}, for each received bit prior to finite integration operation. Therefore, the received data bit can be decoded as

$$\hat{r} = \mathrm{sgn}\left(\int_{T_{in}} r(t - D).z(t)\,dt\right) \qquad (2)$$

The details of each unit are discussed in the following subsections.

A. SNR Enhancing Unit

The SNR enhancing unit actively suppresses various types of non-UWB interference in TR receivers while preserving the desired UWB signal. This unit is comprised of a feedback loop interference mitigation mechanism that was introduced and discussed thoroughly in [5]. Thus, in this paper we briefly review feedback loop mechanism and it's important parameters that directly affect the window estimation performance. Considering the diagram in Fig. 4, the output of the SNR enhancing unit, $z(t)$, can be expressed as

$$z(t) = \sum_{q=0}^{Q} \alpha^{q} r(t - qT) \qquad (3)$$

Where Q represents the number of loop iterations, α denotes the loop loss factor, $r(t)$ is the received signal, and finally T represents the symbol repetition period in TR receivers and is the amount of delay used in the feedback loop mechanism. Due to the averaging effect of the feedback loop, the reference pulses in TR doublets overlap and experience a resonance while the noise being uncorrelated cancels with each loop iteration. Fig. 5 shows the noise suppression effect of the SNR enhancing unit based on number of loop iterations.
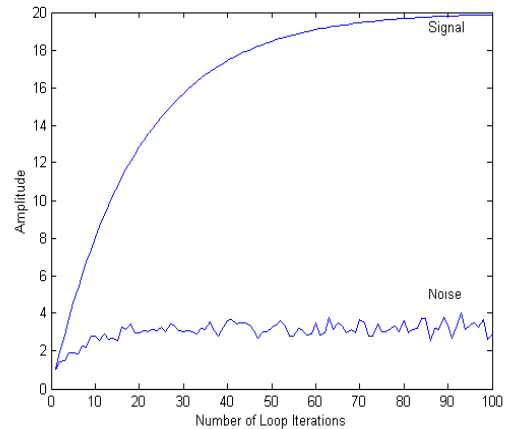

Figure 4: Block diagram of a modified TR receiver with integration window capability

Figure 5: Signal and noise progression at the output of SNR Enhancing unit

The feedback loop mechanism always works well for signals corrupted by AWGN channels, since different samples of white noise are uncorrelated. However, for a successful narrowband interference (NBI) rejection, T should not be equal to integer multiples of interfering signal's period to avoid resonating the NBI.

Substituting (3) in (1) we obtain the signal that enters the acquisition and tracking unit as

$$y(t) = r(t-D) . \sum_{q=0}^{Q} \alpha^q r(t-qT) \qquad (4)$$

As shown in (4), the known problem of noise-on-noise correlation in TR receivers does not exist in our proposed receiver due to reference pulse enhancing characteristics of the feedback loop mechanism.

B. Acquisition and Tracking Unit

The acquisition and tracking unit, as shown in Fig. 4, is comprised of a threshold detecting comparator and a counter circuit. The initial acquisition of the integration window is performed by a comparator device that is programmed to detect various values of SNR in dB units given by

$$x(t_i) = |y(t)| > \gamma \qquad (5)$$

Here $y(t)$ is a vector of the signal entering the acquisition and tracking unit as defined by (4) and $x(t_i)$ denotes the first occurrence of $y(t)$ that has passed the threshold limit. Once the first reference pulse in the received signal passes the assigned threshold, it's timing can be recorded as T_1 and T_2 for the location of the first integration window. Therefore, t_i represents the time index of the first pulse passing the threshold limit. The initial acquisition of the integration window is achieved as the lower limit of the first window, equal to t_i as shown in (6) and Fig. 5.

$$T_1 = t_i \qquad (6)$$

$$T_2 = T_1 + T_p \qquad (7)$$

where T_p represents the duration of pulse energy which is approximately equal to pulse width in LOS channels. Fig. 6 illustrates how the SNR enhancing unit and the threshold comparator provide the initial acquisition of the integration window in TR receivers.

By obtaining the first position of the integration window, the initial acquisition takes place and since the TR doublets are separated by a fixed interval, T, the fine synchronization or tracking operation starts by searching for the specified threshold every T units in time. This process maintains the integration window estimation through the duration of the transmission.
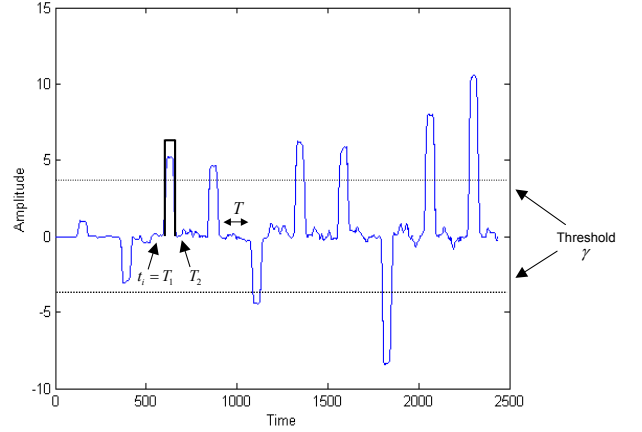

Figure 6: An example of pulses passing through the threshold comparator. The time index for the first pulse passing throught the threshold determines the lower limit for initial acquisition of the integration window

The initial acquisition of the integration window involves some search for the first signal with SNR of larger than the specified threshold. However, this search ends quickly after 15 or 20 loop iterations that corresponds to the loss of 15 to 20 initial received bits. The reason is that the feedback loop mechanism in the SNR enhancing unit improves the signal amplitude rapidly (as shown in Fig. 5) and results in a fast initial acquisition. The initial acquisition and tracking algorithm can be summarized in the following flow chart shown in Fig. 7.
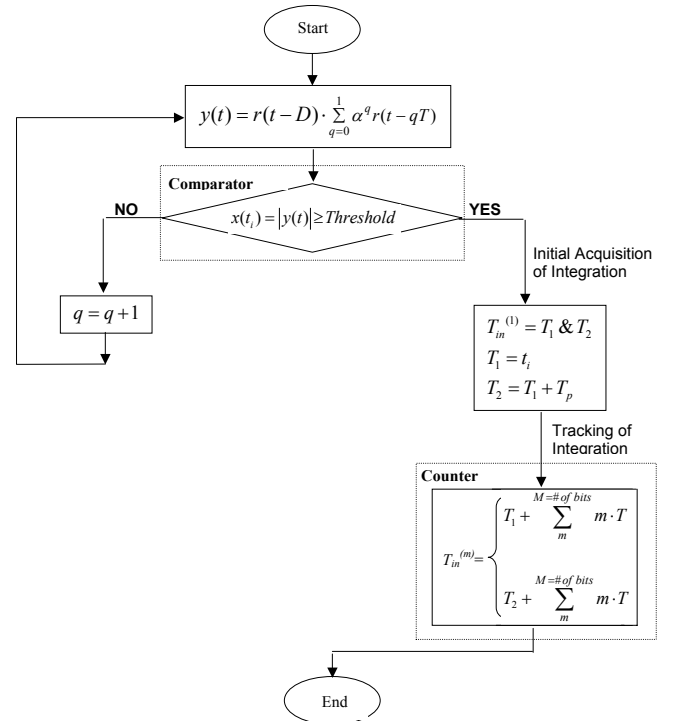

Figure 7: Integration window estimation flow chart

III. PERFORMANCE ANALYSIS

In this section we analyze the performance of a single user TR receiver employing our proposed integration window method. We first show the critical role that SNR enhancing unit has in initial acquisition of the integration window in Fig. 8. In this figure we demonstrate that detection time uncertainty (*Delta_T*) that can be reduced by increasing SNR of the received pulses.
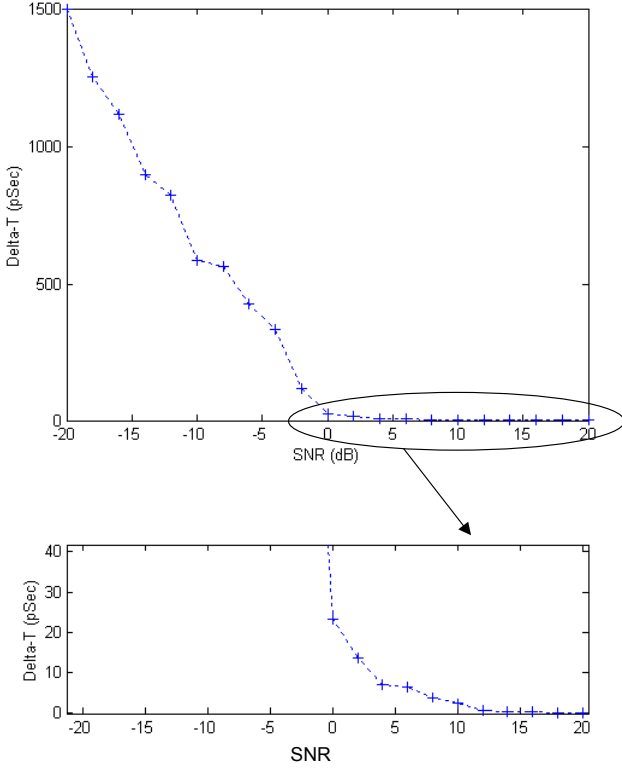

Figure 8: Detection time uncertainty of integration window versus SNR

As shown in the above figure, the time uncertainty in detection of a single pulse decreases from 1.5 ns to 20 ps as the SNR is improved from –20 dB to 0 dB. The bottom portion of the figure shows a zoomed in view of the detection time uncertainty after the SNR is increased from 0 dB to higher values. We can see that the time uncertainty is greatly reduced to almost zero at high SNRs. Therefore, the SNR enhancing unit plays an important role in providing accuracy in detection of the integration window in the presence of timing jitter.

Since the SNR enhancing unit plays an essential role in the initial acquisition of the integration window, we study the receivers BER performance based on the two main parameters of the feedback loop mechanism inside the SNR enhancing unit. These two parameters are number of loop iterations, and loop loss factor, α. In our experiments, we first fix the loop loss factor, α, and study the effect of the number of loop iterations on the BER performance of the modified TR

receiver in MATLAB simulation environment. Once the appropriate number of loop iterations based on the high BER performance is obtained, we fix number of loops and change the value of the loop loss factor to investigate its effect on window estimation performance of TR receivers. The computer simulations presented here are based on a complete asynchronous AWGN channel with random transmission delay for each bit. Fig. 9 shows the BER performance of a modified TR receiver with integration window capability based on various number of loop iterations. In this experiment, the loop loss factor was fixed to the maximum, $\alpha = 0.99$ and a threshold level of 10 dB for the received signal's SNR was selected to achieve the initial acquisition of the integration window.
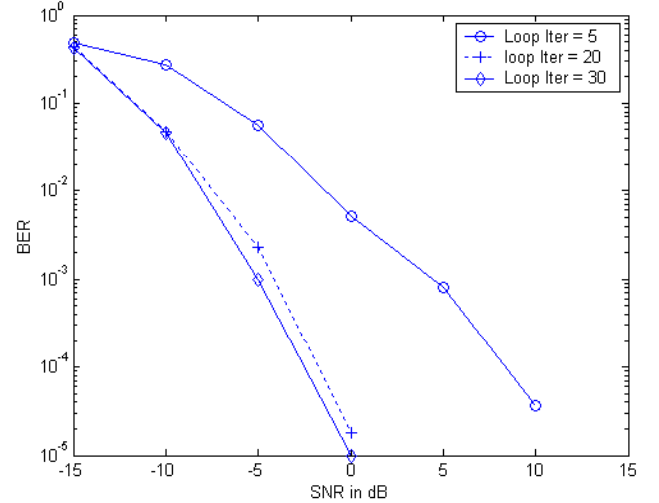

Figure 9: BER versus SNR performance of a modified TR receiver with integration window estimation based on various number of feedback loop iterations. High performance is achieved after 20 iterations and saturates for higher number of loop iterations

As demonstrated in Fig. 9, the synchronization with high performance is achieved after only 20 iterations for 100,000 transmitted bits used in computer simulations. This graph shows that with only 5 loop iterations we obtain bit error rate of 10^{-4} at SNR =10 dB. Further improvement is achieved by increasing the number of loop iterations to 20. However, increasing the number of loop iterations from 20 to 30 provides no further improvements to the BER performance anymore. The reason is that the output of the SNR enhancing unit reaches saturation around 20 iterations.

As explained earlier in this section, for the next part of our experiment, we've fixed the number of loop iterations to 20 and have experimented with different values of loop loss factor to achieve high performance under the same channel conditions as the previous experiment. The threshold limit is set at 10 dB again. Fig. 6-14 shows the BER performance of a modified TR receiver based on various values of loop loss factor for 10 million transmitted bits used in our simulations.
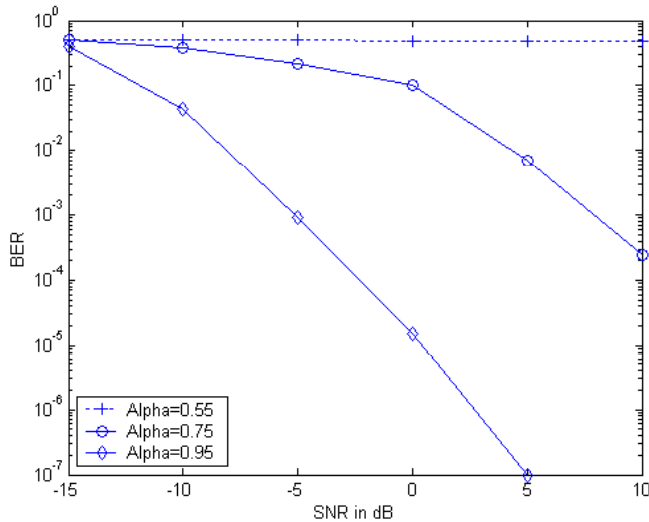
Figure 10: BER versus SNR performance of a synchronized TR receiver based on various values of loop loss factor, α.

As illustrated in the above simulation results, the window estimation capability of the receiver with $\alpha = 0.95$ is superior to that of other α values. However, it is important to remember that the loop loss factor has to be smaller than 1 to assure the stability of the feedback loop in the SNR enhancing unit.

IV. CONCLUSION

The problem addressed in this paper is the precise acquisition and tracking of the position of integration window in TR receivers. We introduced a novel and simple integration window estimation method employing an interference mitigation mechanism to enhance the signal-to-noise-ratio of the received TR modulated signals. This method enhances the received pulses SNR and accurately estimates the integration window to detect each data bit. The effect of improved SNR on reducing the detection time uncertainty was investigated by computer simulations.

The BER versus SNR performance of a TR receiver with the proposed window estimation technique was evaluated based on various parameters of the interference mitigation unit. The analysis reveals that the proposed integration window estimation method has proven to be effective for providing high BER performance in UWB-TR receivers in the presence of non-UWB channel interferences. The method can be extended for window estimation of a multiuser system by assigning a unique symbol repetition period, *T*, to each channel.

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