COARSE ACQUISITION FOR ULTRA WIDEBAND DIGITAL RECEIVERS

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ABSTRACT

Ultra wideband (UWB) radio is a new wireless technology that uses sub-nanosecond pulses to transmit information, resulting in a bandwidth greater than 1 GHz. The problem of synchronizing a receiver with the incoming signal grows in complexity as the signal bandwidth increases. This paper addresses coarse synchronization in UWB receivers. It analyzes how the design of the correlation process affects the time to achieve synchronization, highlighting the importance of the probability of false alarm in its performance.

1. INTRODUCTION

FCC has recently approved UWB for commercial use. UWB represents each bit of information with one or more very narrow pulses which result in a bandwidth greater than 1 GHz. It has been proven [1] that it is possible to obtain data rates over tens of megabits per second while keeping the spectral density of the signal below the noise level, thereof avoiding the disruption of other services that already operate in that band. As the number of bits necessary for this receiver to work has been found to be at most 4 [2], an almost completelly digital implementation is feasible.

The coarse acquisition process provides an initial rough estimation of the signal delay. The complexity and number of operations needed in this estimation increases with the signal bandwidth. In UWB signals the problem is orders of magnitude more difficult than in other wireless modulations like Wideband CDMA or OFDM. A fast acquisition algorithm allows for shorter headers in the data packets and, therefore, increases the effective data rate.

This paper starts with an introduction to UWB signals in section 2. Then, it analyzes the coarse acquisition process in two steps. In the first step, shown in section 3, issues related to the matched filter are studied, such as the choice of a proper signal template and the separation between two consecutive correlations to obtain a reasonable probability of detection. In the second step, presented in section 4, the acquisition process is treated as a Markov process, characterized by the probabilities of detection and false alarm as each possible delay is tested in successive iterations. The last section summarizes the results of this paper.

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2. UWB SIGNALS

Information in a UWB system is typically transmitted using a collection of pulses with widths below $1\ ns$ and a very low duty cycle ($\sim 1\%$) [1]. Each user is assigned a different pseudo-noise (PN) sequence that is used to encode the pulses in either position (PPM) [3] or polarity (BPSK[1]) [4]. Channelization is thus based on the assigned code.

Suppose the bitstream is denoted by a sequence of binary symbols b_j (with values $+1$ or -1) for $j = -\infty, ..., \infty$. A single bit is represented by N_c pulses of width V, where N_c refers to the length of the PN code c_i. For BPSK, the code modulates the polarity of a pulse within each frame. For PPM, the code modulates the pulse positions, incrementing or decrementing them by multiples of V, the width of an individual pulse. Data modulation is achieved by setting the sign of the block of N_c pulses for BPSK. For PPM, we append an additional time-shift τ_{b_j}, whose value depends on the value of b_j. Each frame has duration $T_f = N_f \cdot V$: the duration of each bit is thus given by $N_c N_f V$. Letting A denote the amplitude of each pulse $p(t)$, the transmitted signal can be written, depending on the modulation scheme:

$$s_{BPSK}(t) = A \sum_{j=-\infty}^{\infty} \sum_{i=0}^{N_c-1} b_j c_i p\left(t - jN_cT_f - iT_f\right) \quad (1)$$

$$s_{PPM}(t) = A \sum_{j=-\infty}^{\infty} \sum_{i=0}^{N_c-1} p\left(t - jN_cT_f - iT_f - c_iV - \tau_{b_j}\right) \quad (2)$$

[1] The term BPSK (binary phase-shift keying) is somewhat of a misnomer in the context of an UWB signal: we are basically referring to antipodal signalling, but will continue to use this term for convenience.

The types of pulses that can be used in UWB systems are numerous. For simplicity and to highlight only the aspects related to the dynamics of the synchronization process, only pulses $p(t)$ with no change of sign are used here. The results can be generalized to any kind of pulse using a correlator where the template is a sign signal or a better approximation to the shape of the pulse.

The mathematical expressions of the pulses we will consider, with width V, are:

$$p_{rect}(t) = \begin{cases} 1 & \text{if } |t| < \frac{V}{2} \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

$$p_{triang}(t) = \begin{cases} \frac{2}{V}\left(t - \frac{|V|}{2}\right) & \text{if } |t| < \frac{V}{2} \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

$$p_{gauss}(t) = e^{-\frac{2t^2}{V^2}} \quad (5)$$

3. CORRELATION METHOD: MATCHED FILTER

Optimal detection of a signal in the presence of additive white gaussian noise (AWGN) is based on matched filtering [5]. This entails correlating the incoming signal with a template that is an exact replica of the received pulse. The generation of these replicas of sub-nanosecond pulses is a hard problem, highly susceptible to timing jitter. A simpler approach is to use a template signal comprising a train of rectangular pulses coded with the same PN sequence. As the delay of the received signal is unknown, a discrete number of possible delays of the local template are tested. Figure 1 shows the position of two consecutive rectangular windows around one of the individual pulses received. If the frequencies of the transmitter and receiver clocks are exactly equal, this situation repeats for the N_c pulses received for one bit. This figure also shows the two parameters whose values are needed: the width of the integration window of the receiver (W) and the displacement between two consecutive integration windows (D). W is related to the matched filter concept and obtained for several different kind of pulses. Parameter D is determined from the autocorrelation properties of the pulses received.

3.1. Matched filter: Choice of the integration window

Taking into account the model introduced in the previous section, for each of the pulse shapes defined, there is one optimum value of the width W of the integration window such that the output SNR is maximized. The maximum SNR will occur when the center of the integration window is equal to the center of the pulse. Figure 2 depicts the variation of the SNR with the value of W normalized to the width of the pulse V. The optimum ratio W/V is 1 for a rectangular pulse, $2/3$ for a triangular pulse and 1.4 for a gaussian pulse.

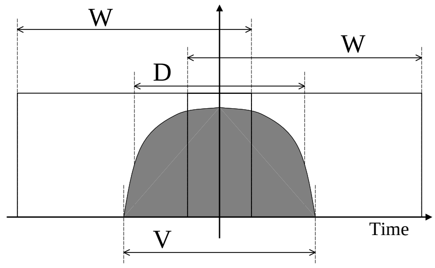

Fig. 1. Situation of two consecutive windows.

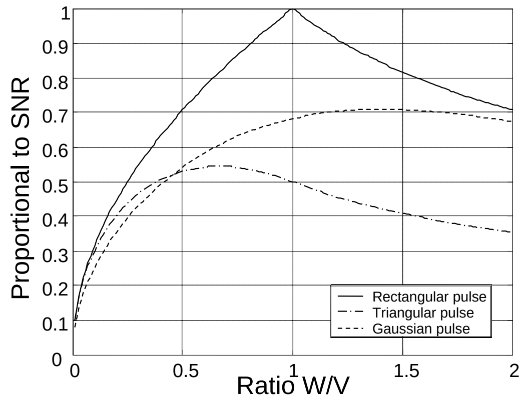

Fig. 2. Relation of SNRs in function of the ratio W/V

3.2. Definition of P_d and P_{fa}

Each time a complete correlation of what could be the UWB representation of a bit is obtained, its output is compared to a threshold in order to check if the UWB signal is present. A issue to consider is that a sign reversal of the whole signal is possible due to the absence of the direct path and the presence of echoes coming from reflectors. To take this into account, the absolute value of the correlation is taken and its result compared to the threshold.

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

$$P_{fa} = 2N\left(\frac{T_h}{\sigma}\right) \text{ with } N(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-\frac{t^2}{2}}dt \quad (6)$$

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. Then there are two parameters of importance for determining both P_{fa} and P_d. Figure 3 shows how the probability of detection for the same SNR decreases with P_{fa}.

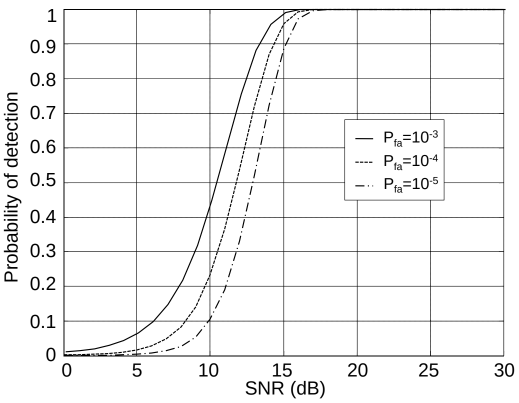

Fig. 3. P_d with the ratio T_h/σ as parameter.

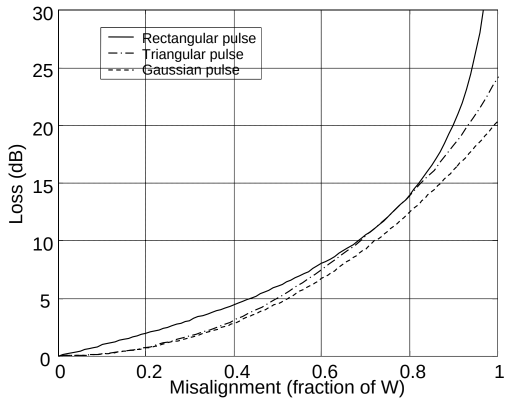

Fig. 4. Loss in SNR due to misalignment of the window.

3.3. Specification of the value of D

In the previous section the SNR was maximized when the center of the pulse and the center of the integrating window were aligned. In reality the output is sampled at a sampling rate of $1/D$, with D being the interval between two consecutive samples. Under this assumption, the probability of coincidence between the center of the integration window and the center of the pulses is zero.

The SNR decreases when the integration window and the pulse are not aligned. In Figure 4, the loss in SNR due to this misalignment is depicted for each of the pulses.

The value of D determines how many opportunities we have to detect the same pulse. It is desirable to minimize the number of integration intervals in which the pulse is present in order to minimize the clock frequency of the correlators. Still, it is also important to ensure a minimum probability of detection when part of the pulse is included in the inte-

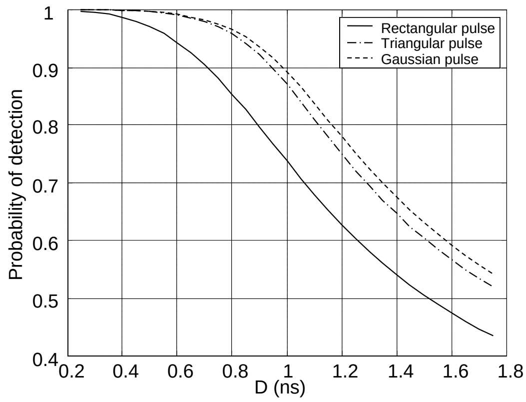

Fig. 5. P_d in one of the two integration windows where part of the pulse is present as a function of D.

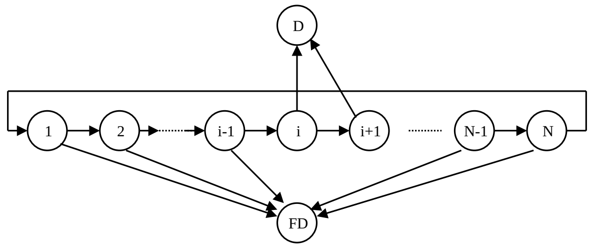

Fig. 6. Coarse acquisition process as a Markov chain.

gration window. Figure 1 shows the position of two consecutive windows with respect to a pulse centered right in between. We can define r as the delay of the pulse with respect to the center of the first integration window. The possible values of r are from 0 to D. The probability of detection when the algorithm sweeps the possible delays from 0 to $N_c N_f V$ is the probability of detecting the pulse in at least one of the two windows that include it. Figure 5 shows the value of this probability as a function of D, averaged for all possible values of r. Setting D equal to W gives a reasonable probability of detection of around 0.90 for both triangular and gaussian pulse while the value for the rectangular pulse falls below 0.9 as its energy is more concentrated. This analysis and the fact that this choice simplifies the timing design in the receiver as all clocks have the same frequency, encourage setting $D = W = 1$.

4. COARSE ACQUISITION PROCESS MODEL

This section will first define an abstract model of the coarse acquisition process. Under some very simple assumptions it can be seen as a Markov chain. Using the values obtained in section 3, the effect of the SNR and the shape of the pulse on the expected time to synchronization ($E[k]$) and the probability of correct detection (P_{cd}) will be examined.

4.1. Coarse acquisition as a Markov chain

The initial assumption is that the position of the pulse with respect to the integrating windows, r, does not change from one pulse to the next inside a bit. This is reasonable since transmitter and receiver clocks have the same frequency. Later on, Bayes theorem will be used to take into account all the possible values of r.

The model of the coarse acquisition process can be seen in Figure 6. In each of the states depicted (except for FD and D) a template with that delay is correlated to the received signal. The initial state can be any from state 1 to state $N = N_c \cdot N_f$. The states i and $i+1$ contain the pulses almost properly aligned. If the pulse is detected there, it goes to state D, correct detection (with probabilities $P_{d,i}$ or $P_{d,i+1}$). The rest of the states do not contain the pulses. Any detection in those states implies a false detection (state FD) with probability P_{fa}. It no signal is detected, from each state it can only jump to the next one.

4.2. PMF for coarse acquisition

We can define a discrete random variable k that represents the number of integration windows examined before declaring a detection. It is assumed that the probabilities of declaring a detection for the slots j from 1 to N is P_j. The probability mass function (PMF) of k can be expressed as:

$$Pr[k] = Pr[n + m \cdot N] = Pr[n]\,\Delta^m = P_n \Delta^m = \prod_{j=1}^{n-1} (1 - P_j) \quad (7)$$

with $\Delta = \prod_{j=1}^{N} (1 - P_j)$. Using this information,

$$E[k] = \frac{\Delta + \sum_{n=1}^{N} nPr[n]}{1 - \Delta} \quad (8)$$

$$P_{cd} = \frac{(P_i + P_{i+1}(1 - P_i)) \prod_{j=1}^{i-1} (1 - P_j)}{1 - \Delta} \quad (9)$$

These results have been obtained assuming a fixed value of r. Using Bayes theorem for both the position i in the chain and r with respect to the integration window, and choosing $N_c = 31$ and $N_f = 50$, we obtain table 1. The average of k is given as the number of decisions or states examined. It is observed that the probability of correct detection drops sharply when $P_{fa} = 10^{-3}$. This happens because P_{fa} is comparable to $1/N$, and in N trials, more than one false alarm will usually arise. Then, in order to ensure a reasonable probability of correct detection, P_{fa} must be lower than $1/N$.

Table 1. Model results

	Rect.		Triang.		Gauss.	
P_{fa}	$E[k]$	P_{cd}	$E[k]$	P_{cd}	$E[k]$	P_{cd}
10^{-3}	1930	0.42	1988	0.47	2016	0.48
10^{-4}	903	0.87	927	0.90	942	0.91
10^{-5}	801	0.98	809	0.99	821	0.99

5. CONCLUSION

In this paper we have analyzed the specification of the coarse synchronization process for an UWB system. The quest for simplicity has led to the use of an integration window instead of a perfect replica of the pulse. The system of using non-overlapping windows to detect a peak of correlation works with reasonable probability of error for triangular and gaussian pulses, while for rectangular pulses it would be necessary to overlap the integration windows. A probability of false alarm below $1/(N_c N_f)$ ensures a reasonable value of P_{cd} and $E[k]$.

6. REFERENCES

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