Performance evaluation of a computationally-efficient acquisition scheme for DS-UWB signals

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Abstract— **Ultra-Wideband (UWB) has been recently promoted as a very promising technology for wireless communications. Rapid and accurate timing acquisition of ultra-short pulses and the high sampling rates required create challenges for both signal acquisition and the overall UWB transceiver implementation, and even more so under non-ideal conditions. In this paper, we evaluate the performance of a computationally-efficient implementation of a DS-UWB acquisition scheme. The suggested rapid acquisition system based on a block-processing technique adapted to a circular frequency domain correlation, shows explicit design characteristics that offer greatly improved acquisition time, accuracy and implementation cost, while also yielding very satisfactory performances at high noise and MAI levels.**

Ultra Wideband Systems; Sequence Acquisition; Impulse Radio

I. INTRODUCTION

Ultra-Wideband technology (UWB), also known as Impulse Radio (IR), has gained a clear and growing interest in recent wireless communications research work. The Federal Communications Commission (FCC) has defined UWB as a wireless transmission scheme that processes an absolute bandwidth larger than 500 MHz or a -10 dB relative bandwidth greater than 20 % of its center frequency [1]. It consists of baseband-transmitting very short duration pulses such that the signal energy is spread over a very large frequency bandwidth with a very low power spectral density. Moreover, UWB is a high data rate transmission technology that can be viewed as an extreme form of spread spectrum techniques [2−4]. It is foreseen today as a possible solution for short-range indoor wireless applications where high resolution, reduced interference, and propagation around obstacles are challenging [5].

Synchronization is known as one of the key technical aspects that influences the successful development of UWB impulse radio. In fact, the extremely narrow time frames and the high sampling rates make signal acquisition and the overall UWB transceiver design/operation a challenging factor from a technical viewpoint [6]. In recent years, much research work has been devoted to accelerating the acquisition process of UWB signals. Based on different algorithmic approaches, several rapid acquisition techniques were proposed [7-15]. However, the complexity aspect was generally less emphasized than the algorithmic one. Indeed, the correlations are computed in the time domain and the acquisition systems are fed by *stream processing*, sample by sample, irrespective of the search strategies used (serial or parallel) [6]. The corresponding architectures are thus not optimal and may require relatively long processing times under challenging conditions.

In this paper, we present a computationally-efficient implementation of an acquisition scheme for DS-UWB signals based on a *block-processing* technique adapted to an FFT-based *high-speed* correlation. The performance of both cubic spline interpolation and zero-padding are provided as references in order to illustrate the benefits of this computationally-efficient acquisition system (with respect to a traditional time-domain acquisition system). The acquisition process is accelerated by handling the dense DS-UWB signal in simultaneous blocks of samples and by reducing the computational cost. For each acquired block, the correlation is computed in the frequency domain by a simple multiplication, while the code phase and the Signal-to-Noise-Ratio (SNR) are estimated.

The remaining content of this paper is organized as follows: The system model is described in Section II. Section III details the proposed baseband UWB computationally-efficient rapid acquisition system. Simulation results are provided in Section IV, followed by concluding remarks in Section V.

II. SYSTEM MODEL

A. Pulse Waveform

The considered ultra-short pulse duration T_c is 2 ns. So the effective UWB signal bandwidth is at least 500 MHz for a *monocycle* first-order Gaussian derivative transmitted pulse. The antenna effect is modeled as a derivation of this transmitted monocycle waveform [2]. Thus the second-order Gaussian derivative is the processed pulse shape at the receiver. The n^{th}-order Gaussian derivative can be expressed by

$$p_n(t) \;=\; \varepsilon_n \,\frac{d^n}{dt^n}\,\exp\!\left[-\,2\pi\!\left(\frac{t}{\tau_p}\right)^{2}\right], \qquad (1)$$

where τ_p represents a bandwidth scaling factor and ε_n is introduced to normalize the energy of the pulses $p_n(t)$. The

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most widely reported pulse in the literature is the second-order Gaussian derivative [3], whose expression is given by

$$p_2(t) = \left[1 - 4\pi\left(\frac{t}{\tau_p}\right)^2\right] \exp\left[-2\pi\left(\frac{t}{\tau_p}\right)^2\right]. \quad (2)$$

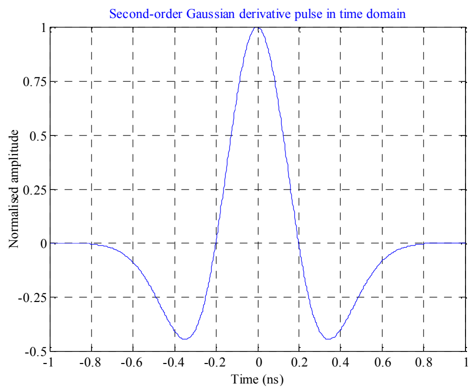

Figure 1. Second-order Gaussian derivative pulse shape.

The autocorrelation $R_2(x)$ of this pulse waveform expressed by $p_2(t)$ in (2) is the following:

$$R_2(x) = \left[1 - 4\pi\left(\frac{x}{\tau_p}\right)^2 + \frac{4\pi^2}{3}\left(\frac{x}{\tau_p}\right)^4\right] \exp\left[-\pi\left(\frac{t}{\tau_p}\right)^2\right]. \quad (3)$$

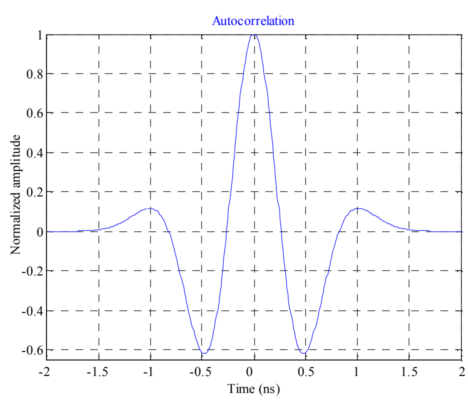

Figure 2. Autocorrelation of the 2nd order Gaussian pulse.

B. DS-UWB System

In this paper, a DS-UWB multiple access system is considered with BPSK antipodal pulse signaling. The duty cycle is 100 % so that the considered pulse waveform occupies the entire chip interval. This used pulse is transmitted continuously according to a spreading code. The transmitted DS-UWB signal by a user k can typically be expressed as

$$s_{tr}^{(k)}(t) = \sum_{j=-\infty}^{j=+\infty} \sum_{n=0}^{N_c-1} d_j^{(k)} \cdot c_n^{(k)} \cdot p_{tr}(t - jT_f - nT_c), \quad (4)$$

where $p_{tr}(t)$ represents the transmitted *monocycle* pulse, $\{d_j\}$ the modulated data symbols[1], $\{c_n\}$ are the spreading chips generated according to a MLS code, and N_c chips per each message symbol j of period T_f − the spreading factor − such that $N_c . T_c = T_f$. When N_u users are active while focusing on the first transmitter, the received signal can be modeled as

$$r(t) = s_{pr}^{(1)}(t - \tau) + n_{tot}(t), \quad (5)$$

where τ is the phaseshift between the transmitter and the receiver and $n_{tot}(t)$ is

$$n_{tot}(t) = \sum_{k=2}^{N_u} s_{pr}^{(k)}(t) + n(t), \quad (6)$$

in which $s_{pr}(t)$ corresponds to $p_{pr}(t)$, the processed pulse shape at the receiver (antenna effect), and where $n(t)$ represents the receiver noise modeled as $N(0, \sigma_n^2)$ with a power spectral density of $N_0/2$. The interfering users are assumed to be perfectly synchronized. Furthermore, as the signals are transmitted over a wireless link, the frame duration is considered far smaller than the channel's coherence time, which means that the fading is quite constant over a large number of frames.

III. Computationally-Efficient Implementation

The *Block-Processing* technique is valuable in view of its efficiency in real time handling of high data throughputs [16]. The method suggested herein for UWB signal acquisition is a direct application of this known technique which has shown high effectiveness [17] [18] in other domains.

For fast and accurate acquisition of UWB signals with optimal receiver complexity, we propose a Block-Processing technique with an *FFT-based high-speed* frequency correlator. The acquisition process is accelerated by handling the dense UWB signal in simultaneous blocks of samples and by reducing efficiently the computational cost. The samples of the acquired UWB signal are stored in blocks as they arrive. The processing of a block starts when its last sample arrives and proceeds simultaneously with the storage of the next block. Block-Processing techniques can be used when the input sample rate is much greater than the output sample rate [16]. For a DS-UWB receiver, processing is performed on each acquired block i to evaluate a code phase-shift τ_i and a Signal to Noise Ratio SNR_i. Since the block must cover at least a whole spreading code period (i.e. several hundred samples), and the output is only two values per block, the conditions for block processing are satisfied.

Synchronization is performed by the FFT-based circular correlator fed by the handled blocks. The block length M is

[1] The data bits are mapped in {-1, 1}.

taken as of power-of-two; thus the used FFTs have an optimal butterfly structure. Hence, the correlation is computed in the frequency domain by a simple multiplication, producing the same result as the standard correlation but faster with this high-speed correlation technique. The fast correlator structure can be further optimized by avoiding the FFT used for the local replica which can be pre-calculated. Therefore, the correlator will require only one FFT/IFFT pair. The processed DS-UWB received signal can be modeled as

$$r_{i,u}^{(j,N_u)} = d_{u,\tau_i}^{(j,k)} c_{i,\tau_i}^{(j,k)} p_{pr}\left((m_i+u) - jT_f - \frac{N_c}{M}(m_i+u)\, T_c - \tau_i\right) + n_{tot_{(i,u)}}^{N_u}, \quad (7)$$

where u refers to the u^{th} sample (u=1, 2, ..., M) of the i^{th} block, m_i the total number of samples before the i^{th} block ($m_i=(i-1).M$) and k corresponds to the acquired user at the receiver.

The block diagram of the proposed UWB fast acquisition system is shown in Fig. 3. Its significant parameters include: a spreading factor N_c=63; a pulse duration $T_p= T_c= 2$ *ns* (a duty cycle of 100 %); number of samples per chip N_s=16 (sampling frequency $F_s= N_s/T_c= 8$ *GHz*); a Gaussian 2nd order derivative as the acquired pulse waveform; and an increased block length $M=(1+N_c).N_s$=1024. An increase method is required for adapting efficiently as possible the acquired block's length to the FFTs of butterfly structure. Thus, the cardinality of the blocks digitized by the ADC converter should be increased from 1008 samples to 1024 (a power-of-two). Then the correlation is calculated in the frequency domain by a fast circular correlator. A peak detector examines its outputs (1024 inverse-FFT outputs) to evaluate the detected peak amplitude and to deduct its position which corresponds to the estimated phase shift τ_i. The more blocks are acquired; the more refined will be that estimated phase. If no peak is detected, the search control block leads the local code generator index to the next pre-calculated replica $k+1$.

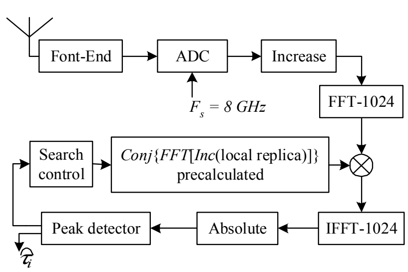

Figure 3. Block diagram of the proposed UWB fast acquisition system.

Assuming that a multiplication computation takes as much as two additions, then the gain in complexity of this proposed fast acquisition scheme (in comparison to a traditional system) can be modeled as:

$$G = -2\cdot 10^{-4} \cdot N_c^{\,2} + 0.47 \cdot N_c + 2.9 \cdot \quad (8)$$

We note for a spreading factor of 63 with N_s=16, a significant reduction in the computational cost by a factor of 32. Consequently, the acquisition time is considerably improved with this computational cost reduction.

IV. Computer Simulation Results

To assess the performance of this computationally-efficient implementation proposed for such a UWB acquisition scheme, numerical simulations were carried out. We present in this section results for four different acquisition systems, including ours. A phase shift of 60 nanoseconds is considered between the transmitter of interest and the receiver with a tolerated time-shift error margin of 4 ns. The rapid acquisition system illustrated in Fig. 3 was simulated in three different forms, with no increase method (non-optimal FFT of 1008 points), with *zero-padding* and finally with *cubic spline interpolation*. An acquisition system based on the standard time-domain correlation was also simulated to compare its performance. Figs. 4 and 5 show the performance degradation of the four simulated UWB acquisition systems, in terms of phase-shift estimation error and correlation peak amplitude when, respectively, the AWGN variance and MAI levels increase. Random and large data vectors were used with a Monte-Carlo technique to compute accurately the system performance. The samples have been chosen here equal to 10^5 and the noise variance was taken σ_n^2=0.3 in the MAI case. In addition, the PN sequences were randomly selected from the six best m-sequences of period 63.

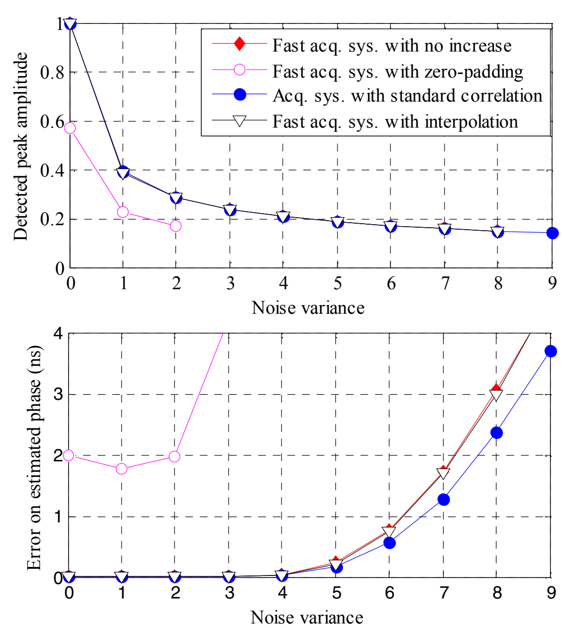

Figure 4. Performance comparison in AWGN case with N_u=1.

From the results, we notice notable performance degradation for the fast acquisition system based on zero-padding. Indeed, this technique changes the circular correlation properties. This is due to the fact that the insertion of the zero divides the MLS code into two subsequences. Thus, the resulting autocorrelation function contains two neighboring peaks instead of one. This energy loss affects the accuracy and the signal detection capabilities and therefore, increases the probability of misdetection.

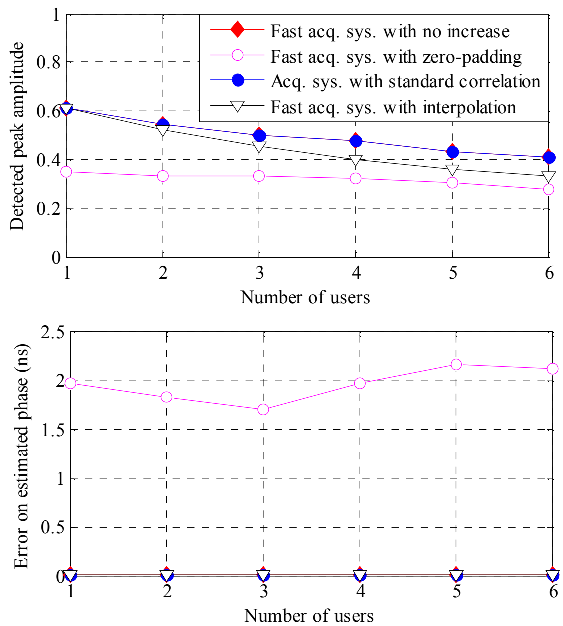

Figure 5. Performances comparison in MAI case with σ_n^2= 0.3.

In the MAI case, we note a more significant impact of the interference on the fast acquisition schemes based on increase methods. This is due to the fact that these techniques change the cross-correlation proprieties of the sequences inducing a loss in energy of the detected peak. However, in both simulated scenarios of AWGN and MAI, the proposed computationally-efficient implementation of the presented DS-UWB acquisition scheme, *based on interpolation as an increase method*, offers acceptable levels of accuracy and detection capabilities, while offering an improved acquisition time with a greatly reduced implementation cost.

V. Conclusion

In this paper, a computationally-efficient implementation of a fast acquisition scheme has been presented for UWB signals. The suggested acquisition system uses a parallel block processing technique with high-speed correlation in the frequency domain. The corresponding system architecture has been optimized and its performance was assessed by its comparison to other acquisition systems. Simulation results have shown that the proposed fast acquisition scheme based on interpolation offers greatly improved implementation cost and acquisition time, while also yielding very satisfactory accuracy performance at high noise and MAI levels.

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