A Computationally Efficient Implementation of a UWB Fast Acquisition Scheme

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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 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 performance 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 growing interest in recent wireless communications research. 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 technique [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 will influence 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 task 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 acquisition systems are fed by *stream processing*, sample by sample, irrespective of the search strategy (serial or parallel) [6]. The corresponding architectures are thus not optimal and may require relatively long processing times under challenging conditions.

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In this paper, we propose 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 cubic spline interpolation and zero-padding are provided as references for comparisons 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 a code phase-shift and a 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. UWB System Model

A. Impulse Waveform

The spectral properties of a UWB system depend on the transmitted pulse waveform. When the Gaussian *monocycle* is the considered transmitted pulse with a very short duration, of typically 1 ns, the energy spreads over a very wide band of at least 1 GHz. While the antenna effect is modeled as a derivation of this transmitted waveform [2], the second-order Gaussian derivative is the processed pulse shape at the receiver. These pulses, illustrated in Fig.1, are easy to generate and have no DC component. The basic Gaussian pulse and its n^{th}-order Gaussian derivative waveforms can be expressed, respectively, as

$$p(t) = \exp\left[-2\pi\left(\frac{t}{\tau_p}\right)^2\right], \tag{1}$$

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

where τ_p represents a bandwidth scaling factor and where ε_n is introduced to normalize the energy of the pulses $p_n(t)$. The second-order Gaussian derivative is the most widely reported pulse in the literature [3]. Its expression can be written as

$$p_2(t) = \left[1 - 4\pi\left(\frac{t}{\tau_p}\right)^2\right] \exp\left[-2\pi\left(\frac{t}{\tau_p}\right)^2\right]. \quad (3)$$

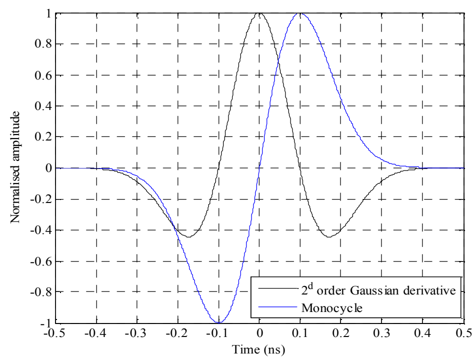

Figure 1. Gaussian Monocycle and Second-order Gaussian derivative waveforms in time domain.

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

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

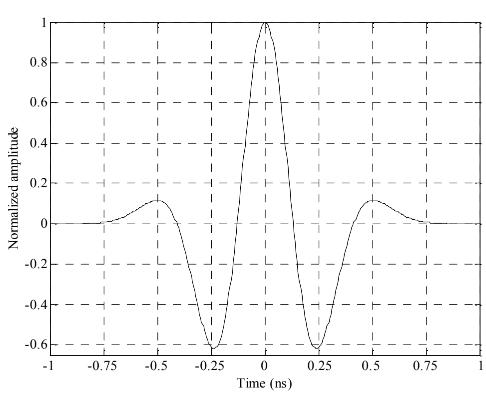

Figure 2. Autocorrelation of the 2nd order Gaussian pulse.

B. System concept

The UWB system considered in this paper employs Direct-Sequence Spread Spectrum (DSSS) as a multiple access approach. DS-UWB uses BPSK antipodal pulse signaling with a duty cycle of 100 % so that the pulse waveform occupies the entire chip interval. This pulse is transmitted continuously according to a spreading code. The DS-UWB signal transmitted by a user k can typically be expressed as

$$s_{tr}^{(k)}(t) = \sum_{j=-\infty}^{j=+\infty} \sum_{n=0}^{N_c-1} d_j^{(k)} \cdot c_n^{(k)} \cdot p_{tr}(t - jT_f - nT_c), \quad (5)$$

where $p_{tr}(t)$ represents the transmitted *monocycle* pulse, $\{d_j\}$ the modulated data symbols mapped into {-1, 1}, $\{c_n\}$ are the spreading chips generated according to a MLS code, T_c is the chip duration, and there are 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

$$r(t) = s_{pr}^{(1)}(t - \tau) + n_{tot}(t), \quad (6)$$

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

$$n_{tot}(t) = \sum_{k=2}^{N_u} s_{pr}^{(k)}(t) + n(t), \quad (7)$$

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. PROPOSED UWB FAST ACQUISITION SCHEME

For fast and accurate acquisition of UWB signals with optimal receiver complexity, a *Block-Processing* technique is proposed with an *FFT-based high-speed* frequency correlator. 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 in other domains [17] [18]. 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. Hence, 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 processed blocks. The block length M is taken as of power-of-two; thus the FFTs have an optimal butterfly structure. Therefore, 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. Then, the correlator will require only one FFT/IFFT pair. The block diagram of the proposed UWB fast acquisition system is shown in Fig. 3. The processed DS-UWB received signal can be modeled as

$$r_{i,u}^{(j,N_u)} = d_{u,\tau_i}^{(j,k)} c_{i,\tau_i}^{(j,k)} p_{pr}\left((m_i+u) - jT_f - \frac{N_c}{M}(m_i+u)\, T_c - \tau_i\right) + n_{tot_{(i,u)}}^{N_u}, \quad (8)$$

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 where k corresponds to the acquired user at the receiver.

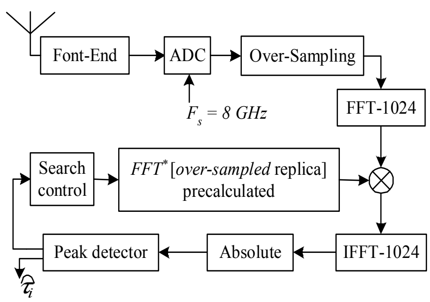

Figure 3. Block diagram of the proposed UWB fast acquisition scheme.

The significant parameters of this computationally-efficient implementation include: a spreading factor N_c=127; a pulse duration T_p= T_c= 1 *ns*; number of samples per chip N_s=8 (sampling frequency F_s= N_s/T_c= 8 *GHz*); a Gaussian 2^{nd} order derivative as the acquired pulse waveform; and increased block length $M=(1+N_c).N_s$=1024. An over-sampling method is required for adapting efficiently as possible the acquired block's length to the butterfly structure FFTs. Thus, the cardinality of the blocks digitized by the ADC converter should be increased from 1016 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 deduce 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*.

Assuming that a multiplication computation takes as much as two additions, then the total required operations by this UWB fast acquisition scheme is $6log_2M+2M$. Thus, the gain in complexity of this proposed computationally-efficient fast acquisition scheme (in comparison to a time domain traditional system) can be illustrated as shown in Fig. 4.

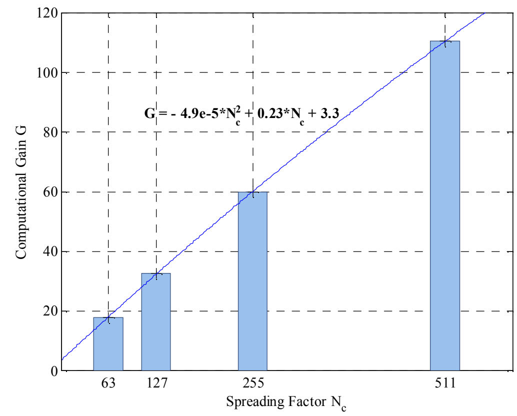

Figure 4. Gain in complexity with respect to the spreading factor for N_s=8.

We note, for a spreading factor of 127, a significant reduction in the computational cost by a factor of about 32. Consequently, the acquisition time is considerably improved with such a computational cost reduction.

IV. Computer Simulation Results

To assess the performance of the computationally-efficient implementation proposed for UWB acquisition, numerical simulations were carried out. We present in this section results obtained for four different acquisition systems, including ours. A phase-shift of 50 nanoseconds is preset between the transmitter of interest and the receiver with a tolerated time-shift error threshold equal to 2 ns. The rapid acquisition system illustrated in Fig.3 was simulated in three different forms, without an over-sampling method (non-optimal FFT of 1016 points), with *zero-padding* and finally with a *cubic spline interpolation*. An acquisition system based on the standard time-domain correlation was also simulated to compare its precision performance. Figs. 5 and 6 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 accurately compute the performance. The number of samples has been chosen here equal to 10^5 and the noise variance was taken to be σ_n^2=1 in the MAI case. In addition, the PN sequences were randomly selected from the best sixteen m-sequences of period 127.

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.

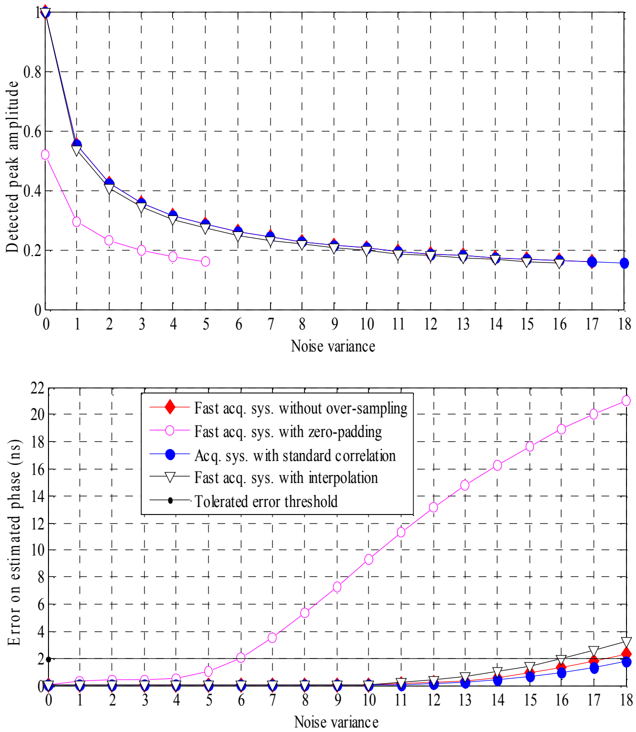

Figure 5. Performance comparison in AWGN case with N_u=1.

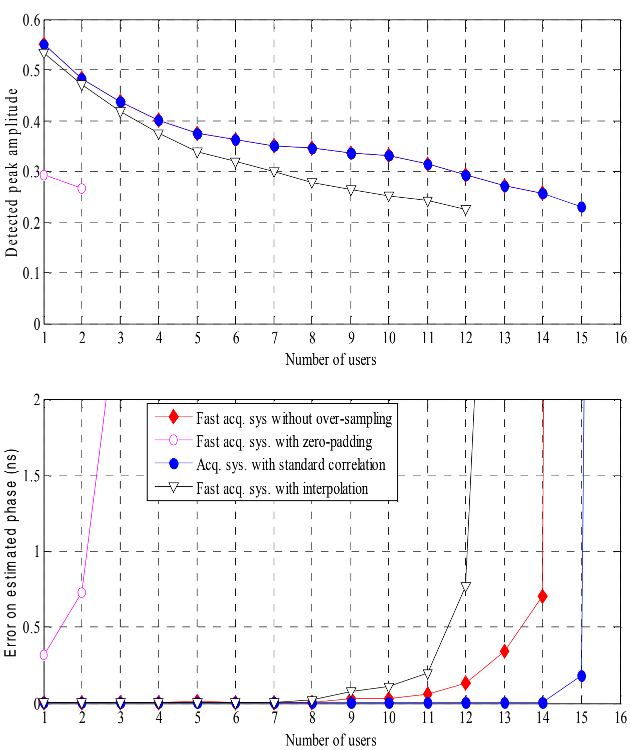

Figure 6. Performances comparison in MAI case with σ_n^2= 1.

In the MAI case, we note a more significant impact of the interference on the fast acquisition schemes based on over-sampling methods. This is due to the fact that these techniques change the cross-correlation properties of the sequences inducting 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 over-sampling 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 proposed 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 performance at high noise and MAI levels.

REFERENCES

[1] Federal Communications Commission "Revision of part 15 of the commission's rules regarding ultra-wideband transmission systems," First Report and Order, ET Docket 98–153, Apr. 2002.

[2] M. Z. Win and R. A. Scholtz, "Impulse radio: how it works," IEEE Commun. Letters, vol.2, pp.36–38, Feb. 1998.

[3] M. Z. Win and R. A. Scholtz, "Ultra-wide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communications," IEEE Trans. Comm., vol. 48, pp.679–690, Apr. 2000.

[4] L. Yang and G. B. Giannakis, "Ultra-wideband communications: an idea whose time has come," IEEE Signal Proc. Magazine, Vol. 21, pp. 26–54, Nov. 2004.

[5] A. Dogandzic, J. Riba, G. Seco and A.L. Swindlehurst, "Positioning and navigation with applications to communications," IEEE Signal Proc. Magazine, vol. 22, pp.10–11, Jul. 2005.

[6] L Reggiani and G.M. Maggio, "On the acquisition time for serial and parallel code search in UWB impulse radio," ISCAS'05. IEEE Int. Sym. On, vol. 1, pp.53 – 56, May 2005.

[7] R. Blazquez, P. Newaskar, and A. Chandrakasan, "Coarse acquisition for ultrawideband digital receivers," in IEEE Proc. 2003 Intl. Conf. Acoustics, Speech and Signal Proc., vol. 4, pp.137–140, Apr. 2003.

[8] S. Soderi, J. Iinatti, and M. Hamalainen, "CLPDI algorithm in UWB synchronization," in Proc. 2003 Intl. Workshop on UWB Systems, pp.759 – 763, Jun. 2003.

[9] E. A. Homier and R. A. Scholtz, "Rapid acquisition of ultra-wideband signals in the dense multipath channel," in Proc. 2002 IEEE Conf. UWB Systems Technology, pp. 105–109, May 2002.

[10] J. Oh, S. Yang and Y. Shin, "A rapid acquisition scheme for UWB signals in indoor wireless channels," in IEEE WCNC'04, Vol. 2, pp.143– 147, Mar. 2004.

[11] S. Vijayakumaran and T. F. Wong, "Best permutation search strategy for ultra-wideband signal acquisition," in Proc. IEEE VTC'04-Fall, Vol. 2, pp.1184– 1187, Sep. 2004.

[12] H. Wang S. Jiang, G. Wei and F. Ji, "A rapid synchronization acquisition scheme for UWB communications," in Systems and Control in Aerospace and Astronautics, ISSCAA'2006. 1st Inter. Sympo. on, pp.844– 848, Jan. 2006.

[13] S. Gezici, E. Fishler, H. Kobayashi, H.V. Poor and A.F. Molisch, "A rapid acquisition technique for impulse radio," in Comm., Computers and Signal Proc., PACRIM'2003, IEEE Pacific Rim Conf. on, Vol. 2, pp.627– 630, Aug. 2003.

[14] L. Reggiani and G. M. Maggio, “A reduced-complexity acquisition algorithm for impulse radio,” in Proc. 2003 IEEE Conf. UWB Systems Technology, pp.131–135, Nov. 2003.

[15] J. Furukawa, Y. Sanada, and T. Kuroda, “Novel initial acquisition scheme for impulse-based UWB systems,” in Proc. 2004 Intl. Workshop UWB Systems, pp. 278– 282, May 2004.

[16] J.G. Ackenhusen, Real-time signal processing: design and implementation of signal processing systems, Prentice Hall, 1999.

[17] P.M. Gerard, G.P.M. Egelmeers and P.C.W. Sommen, “A new method for efficient convolution in frequency domain by nonuniform partitioning for adaptive filtering,” in Signal Proc, IEEE Trans. on, Vol. 44, pp.3123 – 3129, Dec. 1996.

[18] G. Feng and F. Van Graas, “GPS receiver block processing,” in Proc. ION Institute Of Navigation GPS-99, pp. 307– 316, Sep. 1999.