A fast acquisition system for ultra-wideband wireless multiple-access communications

Un système d'acquisition rapide pour des communications sans fil à très large bande et à accès multiple

Yassine Salih Alj, Charles Despins, and Sofiène Affes*

The fast and accurate timing acquisition of short ultra-wideband (UWB) pulse shapes and, implicitly, the required high sampling rates play a significant role in UWB receiver-structure design and create challenges for signal acquisition under non-ideal conditions. Furthermore, the pulse shape is seen as one of the key factors influencing the performance of UWB systems. While fulfilling the power-spectral-density emission requirements, the pulse shape must offer the highest detection capabilities with suitable levels of accuracy. In this paper, a fast acquisition system for UWB wireless multiple-access communications is presented. The proposed acquisition system has explicit design characteristics that offer greatly improved acquisition time, accuracy, and implementation cost, while also yielding very satisfactory performance at high noise and multi-user interference levels. In addition, the impact of pulse shapes on the performance of this fast acquisition system is evaluated to determine the most suitable pulse shape for its implementation.

L'acquisition rapide et précise des impulsions ultracourtes utilisées en communications à très large bande (UWB) et, implicitement, les taux d'échantillonnage élevés requis jouent un rôle important dans la conception du récepteur UWB et créent des défis pour l'acquisition du signal dans des conditions non-idéales. La forme d'onde est, en outre, perçue comme un des principaux facteurs qui influencent les performances des systèmes UWB. Celle-ci doit permettre d'obtenir de bonnes capacités de détection avec des niveaux de précision appropriés, et ce tout en respectant les conditions d'émission de la densité spectrale de puissance. Cet article présente un système d'acquisition rapide du signal UWB pour des communications sans fil à accès multiple. Le système proposé offre des caractéristiques explicites de conception qui promettent des temps d'acquisition, précision et complexité considérablement améliorés, et ce tout en conservant des performances assez satisfaisantes à des niveaux élevés de bruit et d'interférence entre usagers. L'impact de la forme d'onde sur les performances du système est également évalué, et ce, afin de déterminer l'impulsion la plus appropriée pour son implantation.

Keywords: pulse shape; sequence acquisition; ultra-wideband

I Introduction

Ultra-wideband (UWB) radio is a fast-emerging technology, currently regarded as an attractive solution for many wireless communication applications. As a carrier-free (baseband) wireless transmission technology, UWB radio utilizes ultra-short waveforms that are compatible with Federal Communications Commission (FCC) spectral masks. The resulting transmitted UWB signal is spread with a very low power spectral density (PSD) over an absolute bandwidth of at least 500 MHz into a large spectrum (3.1–10.6 GHz) [1]. Moreover, UWB is a high-data-rate transmission technology that can be viewed as an extreme form of a spread-spectrum technique [2]–[4]. It is viewed today as a possible solution for short-range indoor wireless applications where high resolution, reduced interference, and propagation around obstacles are challenging [5].

Timing acquisition is known to be one of the key technical aspects influencing the successful development of UWB systems. In fact, the extremely narrow time frames and the high sampling rates required 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 fast acquisition techniques have been proposed [7]–[15]. However, the complexity aspect has generally been 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.

In this paper, a UWB fast acquisition system based on a block-processing technique adapted to a fast Fourier transform (FFT)–based high-speed correlation is presented. The performances of cubic spline interpolation and zero padding are provided as references for comparison to illustrate the benefits of this computationally efficient acquisition system (with respect to a traditional time-domain acquisition system).

Furthermore, the choice of the fundamental pulse shape used to generate a UWB signal is a key consideration [16]. In fact, the pulse shape used within the proposed UWB acquisition system may affect the system performance. In [17], the first 10 Gaussian derivatives are compared in terms of their PSD and compliance with the FCC spectral constraints. For these pulses, higher-order derivatives are shown to offer a better fit to the FCC masks with a decreasing bandwidth as the order of the derivatives increases. Moreover, Gaussian-based pulse shapes generally outperform other typical UWB pulse types, as

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recently proposed in [18], and are noticeably easier to generate [19]. These observations lead to the consideration of Gaussian-based pulse shapes, typically high-order derivatives, as the most likely candidates for the proposed UWB system. The performance levels of the first 11 Gaussian derivatives and the popular doublet waveform are compared in this paper to determine the most suitable pulse shapes for the implementation of this fast acquisition scheme.

The remainder of this paper is organized as follows. In Section II, the characteristics of the Gaussian-based impulses are briefly highlighted, and the system concept is described. Section III details the proposed UWB fast acquisition system. Simulation results are provided in Section IV, and Section V concludes the paper.

II System model

II.A Pulse shape

The transmitted pulse shape used within a UWB system influences its spectral properties. However, because of antenna effects, the processed pulse at the receiver is modelled as a derivative of the transmitted pulse shape. The basic Gaussian pulse is expressed as

$$p(t) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{t^2}{2\sigma^2}\right), \quad (1)$$

where σ is a shape factor typically used as a bandwidth decaying parameter. The n-th–order Gaussian derivative (see Fig. 1) can be determined recursively from

$$p_n(t) = -\frac{n-1}{\sigma^2} p_{n-2}(t) - \frac{t}{\sigma^2} p_{n-1}(t). \quad (2)$$

The amplitude spectrum of the n-th–order Gaussian derivative, obtained from its Fourier transform, is

$$|X_n(f)| = (2\pi f)^n \exp\left\{-\frac{(2\pi f \sigma)^2}{2}\right\}. \quad (3)$$

By differentiating (3) and setting it equal to zero, one can find the peak transmission frequency f_p at which the maximum is attained, to satisfy the following:

$$2\pi f_p \sigma = \sqrt{n}. \quad (4)$$

Then, the Gaussian derivatives of higher orders are characterized by a higher peak frequency, and reducing the shape factor σ shortens the pulse. The parameters σ and n can thus be chosen to satisfy the FCC masks. Notice that the PSD of the first-order Gaussian derivative does not meet the FCC requirement no matter what value of pulse width is used. Moreover, increasing the order of the derivative results in a wider overall pulse width for each successive pulse and, consequently, within a narrower bandwidth around the same centre frequency, thereby providing a better fit to the FCC masks. Indeed, as the pulse order increases, the number of zero crossings in the same pulse width also increases. The pulses then begin to resemble sinusoids modulated by a Gaussian pulse-shaped envelope, thus corresponding to a higher "carrier"-frequency sinusoid modulated by an equivalent Gaussian envelope [16].

II.B System concept

The direct-sequence (DS) UWB concept is employed in this paper with BPSK pulse signalling. The pulse occupies the entire chip interval and is transmitted continuously according to a maximum-length sequence (MLS) spreading code. The DS-UWB signal transmitted by a user k can typically be expressed as

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

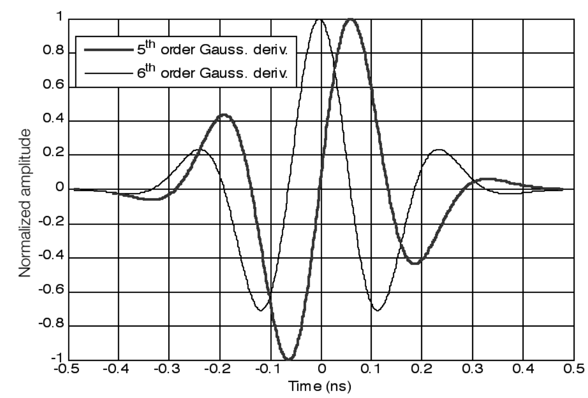

Figure 1: *Fifth- and sixth-order Gaussian-derivative pulse shapes in time domain.*

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

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

where τ is the phase shift between the transmitter and the receiver and $n_{\mathrm{tot}}(t)$ is defined as

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

where $s_{\mathrm{pr}}(t)$ corresponds to $p_{\mathrm{pr}}(t)$, the processed pulse shape at the receiver (antenna effect), and where $n(t)$ represents the received Gaussian noise modelled 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 (i.e., Gaussian channel), 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. Note that a complex tap model is not adopted for the Gaussian channel considered herein. The complex baseband model is a natural fit for narrowband systems to capture channel behaviour independently of carrier frequency, but this motivation breaks down for UWB systems, where a real-valued simulation at RF may be more natural [20]. In this paper, the interference source of the channel is assumed to be limited to the additive white Gaussian noise (AWGN) used.

III DS-UWB fast acquisition system

For fast and accurate acquisition of UWB signals with optimal receiver complexity, a block-processing technique with an FFT-based high-speed frequency correlator is proposed. The block-processing technique is valuable in view of its efficiency in real-time handling of high data throughputs [21]. The method suggested herein for UWB signal acquisition is a direct application of this known technique, which has shown high effectiveness [22]–[23] in other fields. The acquisition process is accelerated by handling the dense UWB signal in simultaneous blocks of samples and by efficiently reducing 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 [21]. For a DS-UWB receiver, processing is performed on each acquired block i to evaluate a code phase

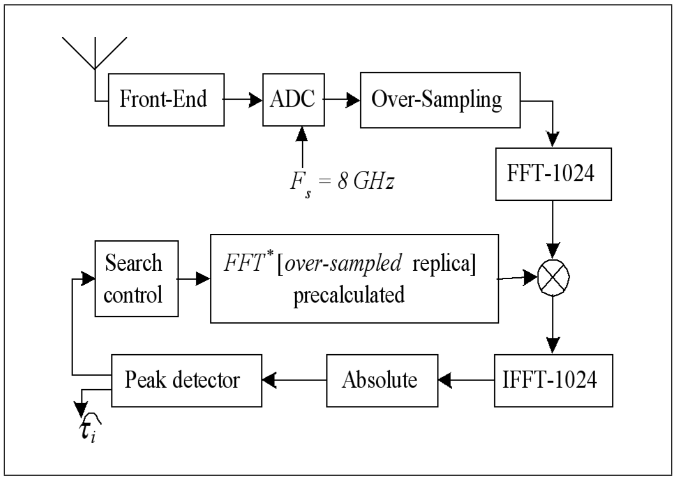

Figure 2: *Block diagram of the UWB fast acquisition system.*

shift τ_i and a signal-to-noise ratio SINR_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.

Timing acquisition is performed by the FFT-based circular correlator fed by the handled blocks. The block length M is taken as a power of two; therefore 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 more quickly, thanks to 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 precalculated), so that the correlator will require only one FFT/inverse FFT pair. The processed DS-UWB received signal can be modelled as

$$r_{i,u}^{(j,N_u)} = d_{u,\tau_i}^{(j,k)} c_{i,\tau_i}^{(j,k)} p_{\mathrm{Pr}} \left((m_i + u) - jT_f - \frac{N_c}{M}(m_i + u)T_c - \tau_i \right) + n_{\mathrm{tot}_{(i,u)}}^{N_u}, \tag{8}$$

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

The block diagram of the proposed UWB fast acquisition system is shown in Fig. 2. Its significant parameters include a spreading factor $N_c = 63$; pulse duration $T_p = T_c = 2\,\mathrm{ns}$ (a duty cycle of 100%); number of samples per chip $N_s = 16$ (sampling frequency $F_s = N_s/T_c = 8\,\mathrm{GHz}$); a Gaussian second-order derivative as the acquired pulse waveform; and an increased block length $M = (1 + N_c)N_s = 1024$. It should be noted that recent developments in research institutions and industry promise high sampling rates with great resolutions for both analogue-to-digital converters (ADCs) and FFTs [24]–[25]. Moreover, the values of these parameters were chosen for a multiple-access level offered by the spreading factor used with the possible sampling rates and resolutions for a bandwidth of 500 MHz.

An oversampling method is required to adapt the acquired block's length to the FFT's butterfly structure as efficiently as possible. 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 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 precalculated replica $k + 1$.

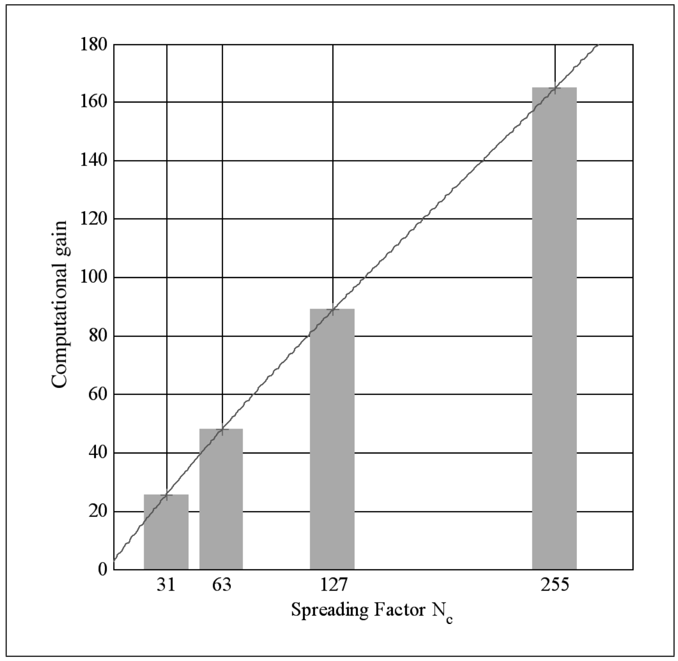

Figure 3: *Gain complexity with respect to the spreading factor for $N_s = 16$.*

If a multiplication computation is assumed to take as much computational time as two addition operations, then the number of operations required by this UWB acquisition scheme is $6M \log_2 M + 2M$. Thus, the gain in complexity of this proposed fast DS-UWB acquisition system (in comparison to a traditional system, which requires M^2 multiplications and $M^2 - 1$ addition operations) can be illustrated as shown in Fig. 3.

Accordingly, by using interpolation fitting, one can model the obtained gain in complexity in terms of the used spreading factor as

$$G = 1.5 \cdot 10^{-6} N_c^3 - 9.2 \cdot 10^{-4} N_c^2 + 0.77 N_c + 2.6. \tag{9}$$

It should be noted that for a spreading factor of 63, there is a significant reduction in the computational cost by a factor of 48. Consequently, the acquisition time is considerably improved with a computational cost reduction.

IV Simulation results

To assess the performance of this computationally efficient implementation of a UWB acquisition scheme, numerical simulations were carried out. This section presents performance comparisons for four different acquisition systems, including the proposed system. Moreover, the performances of the first 11 Gaussian derivatives and the doublet waveforms used as pulse shapes within the proposed fast UWB acquisition system are compared. To ensure an effective bandwidth of at least 500 MHz, the common pulse width is taken to be 2 ns. Under conditions of Gaussian noise and multi-user interference (MUI), a phase shift of 60 ns is preset between the transmitter of interest and the receiver with a tolerated time-shift error threshold equal to 4 ns.

The fast acquisition system illustrated in Fig. 2 was simulated in three different forms: without an oversampling 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 when the noise variance and MUI levels, respectively, increase the performance degradation of the four simulated UWB acquisition systems in terms of phase-shift estimation error and correlation peak amplitude (i.e., normalized SINR), computed using MATLAB software. These performance indices correspond to the

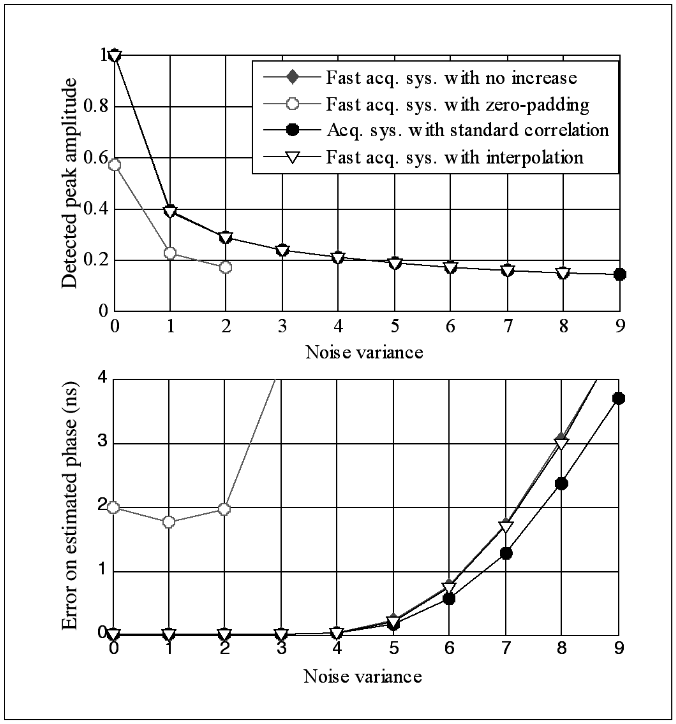

Figure 4: *Performance comparison in AWGN case with* $N_u = 1$.

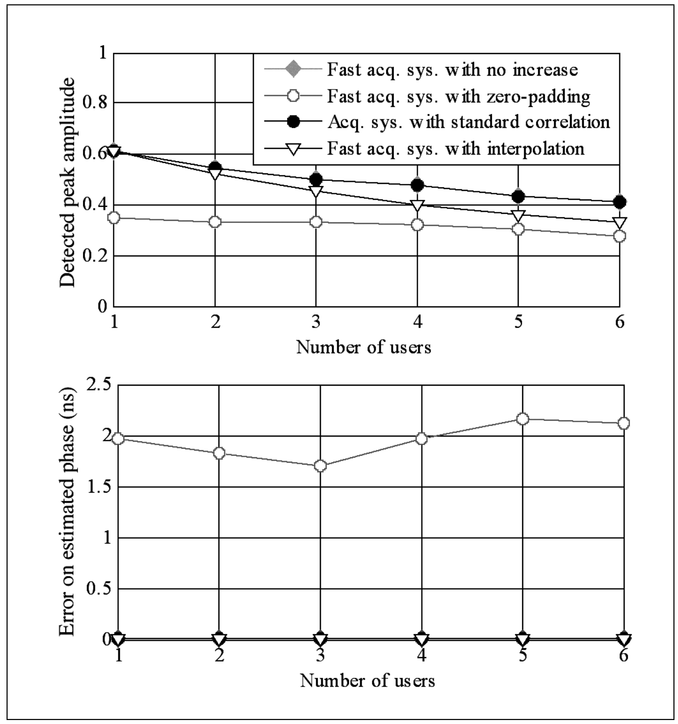

Figure 5: *Performance comparison in MUI case with* $\sigma_n^2 = 0.3$.

overall detection capabilities, as the BER cannot be quantified during despreading since an absolute operation is applied at the complex outputs of the fast correlator. Random and large data vectors were used with a Monte Carlo technique to accurately compute the system performance. The samples were chosen here to equal 10^5, and the noise variance was taken to be $\sigma_n^2 = 0.3$ in the MUI case. In addition, the pseudo-noise (PN) sequences were randomly selected from the six best m-sequences of period 63.

From the comparison results illustrated in Figs. 4 and 5, a notable performance degradation can be observed for the fast acquisition system based on zero padding. Indeed, this technique changes the circular correlation properties, due to the fact that the insertion of the zero divides the MLS code into two subsequences, such that the resulting autocorrelation function contains two neighbouring peaks instead of one. Fig. 6 illustrates the obtained autocorrelation function of a zero-padded pulse train showing the two neighbouring peaks around the phase shift of 60 ns. This observed energy loss affects the accuracy and the signal detection capabilities, thus increasing the probability of misdetection.

In the MUI case (i.e., Fig. 5), a more significant impact of the interference on the fast acquisition schemes based on oversampling methods can be noted. This effect is due to the fact that these techniques change the cross-correlation properties of the sequences, inducing a loss in energy of the detected peak. For the system based on zero padding, the obtained phase-shift error fluctuates slightly with respect to the strongest peak detected between the two neighbouring peaks in the resulting autocorrelation function. However, in both the AWGN and MUI simulated scenarios, the proposed computationally efficient implementation of the presented fast DS-UWB acquisition system, based on interpolation as an oversampling method, offers acceptable levels of accuracy and detection capabilities, while offering an improved acquisition time with a greatly reduced implementation cost.

As noted, the cubic spline interpolation used as an oversampling technique changes the overall correlation properties (e.g., peak amplitude) of the pulse shape. Hence, the pulse shapes will behave differently here than in other standard acquisition systems. The considered first 11 Gaussian derivatives and the doublet pulse shapes were run in extensive Monte Carlo simulations and compared while the noise

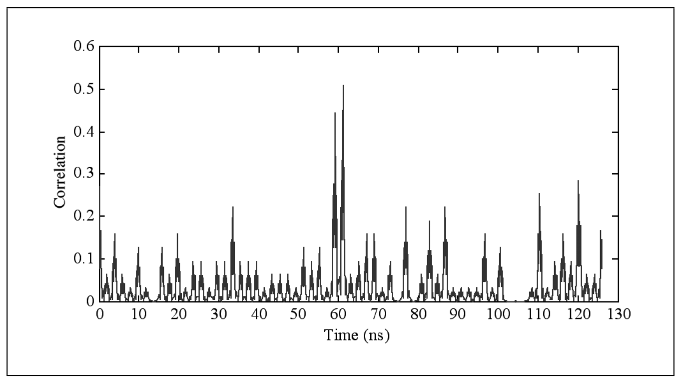

Figure 6: *Autocorrelation function for a zero-padded pulse train.*

variance was taken as $\sigma_n^2 = 2$ in the MUI case. Figs. 7 and 8 show the performance degradation of the simulated waveforms within the proposed fast acquisition system in terms of correlation peak amplitude and phase-shift estimation error when, respectively, the AWGN variance and MUI levels increase.

It is noted that the best performance score is obtained by the eighth-order Gaussian derivative and that a slightly lower level is achieved by the sixth-order derivative. One can also note a more severe impact of the MUI on the doublet pulse shape. It was observed for the three first-order derivatives, irrespective of their performance, that they do not meet the FCC spectral masks [26] and cannot satisfy the FCC requirements, regardless of the pulse duration. Therefore, it is concluded that the sixth- or the eighth-order Gaussian derivative is the most suitable pulse shape to choose, depending on the spectral bandwidth requirements, since the sixth-order derivative offers a wider bandwidth. Indeed, as the derivative order increases, the peak transmission frequency increases and the signal bandwidth decreases. Hence, the choice of the most appropriate derivative order is a tradeoff with the pulse shape factor for a desired performance level. Bandwidth maximization is also an important factor when choosing the derivative order of the UWB pulse transmission [19]. On the basis of these observations, the sixth-order Gaussian derivative has been chosen for the proposed UWB fast acquisition system.

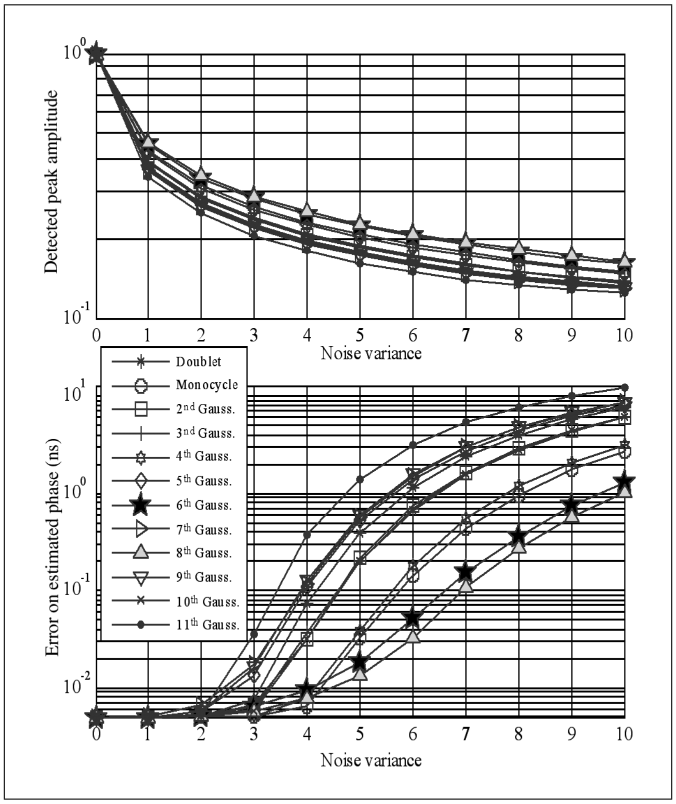

Figure 7: *Performance comparison under Gaussian noise without MUI.*

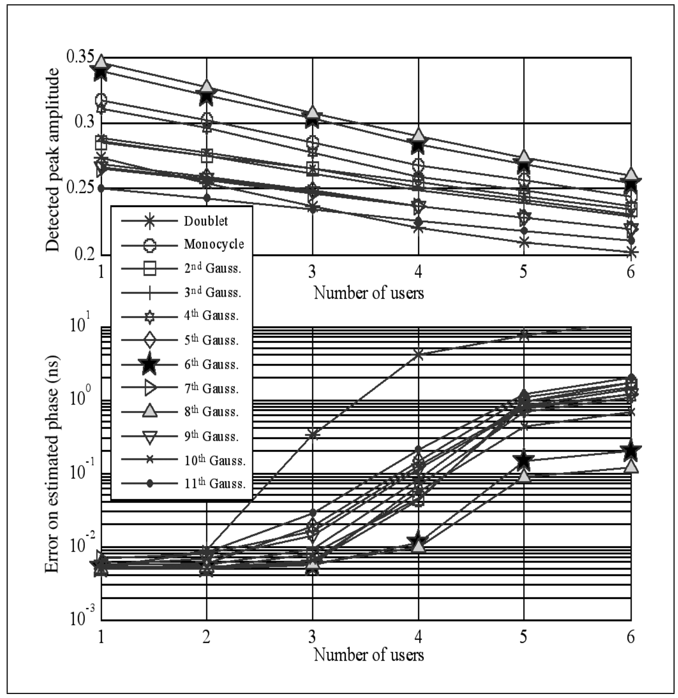

Figure 8: *Performance comparison under MUI and Gaussian noise ($\sigma_n^2 = 2$).*

V Conclusion

In this paper, a fast acquisition scheme has been proposed for UWB signals. The suggested computationally efficient implementation of this fast 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 has been assessed in 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 MUI levels. Furthermore, the effect of pulse shapes on the performance of this new UWB fast acquisition scheme has been evaluated. Different Gaussian-based pulses were compared in extensive Monte Carlo simulations. The results have shown that the choice of pulse shape has a clear impact on the performance of the proposed UWB fast acquisition scheme, and it was concluded that the sixth- and eighth-order Gaussian derivatives are the most suitable pulse shapes to adopt in this system, depending on spectral bandwidth requirements. Finally, taking into account the spectral bandwidth maximization as an important design factor, the sixth-order Gaussian derivative has been chosen in this work.

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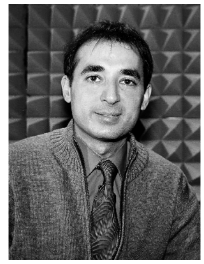

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