Blind Algorithms for Timing Acquisition of Impulse Radio UWB Communications

Stéphane Azou[1,2] and Emanuel Rădoi[1,2]

[1]*Université Européenne de Bretagne, France.*
[2]*Université de Brest ; CNRS, UMR 6285 LabSTICC ; Brest, France*

*E-mails : {azou, radoi}@univ-brest.fr

***Abstract*—This paper deals with timing recovery for Impulse Radio (IR) ultra-wideband (UWB) communication systems, which is known to be a challenging task to accomplish. We focus on blind estimation approaches, with the aim of being able to operate with minimal constraints on the signal format (no use of pilot symbols). We consider also the blind timing estimation problem in the sense that no prior knowledge is needed on the modulation parameters. The proposed methods may contribute to develop flexible receivers, capable of synchronizing various IR-UWB signal formats from short data records, even if some key parameters are changed over time.**

***Keywords* – UltraWideband, Impulse Radio, Time-Hopping, Synchronization, Timing acquisition, Blind estimation, Nonlinear optimization, Energy detection.**

I. Introduction

Since its approval by the U.S. Federal Communications Commission (FCC) in 2002, Impulse Radio - UWB (IR-UWB) has given rise to considerable interest in wireless communications research community, due to its many attractive properties [1]. Today, IR is considered as a promising technique from an industrial perspective [2]; in particular, it is a main candidate solution for applications such as wireless sensor networks [3] due to its ability to provide joint data transmission and precise positioning [4] at short distances. However, a number of system design challenges remain to be solved to ensure a broader use of IR-UWB communications in practice [5], due to the very fine time resolution and low power of transmitted pulses : waveforms distortions (due to transmitting/receiving antenna), clock jitter and time-variant frequency-selective channel with rich multipath. Whatever the receiver architecture, a synchronization block must provide accurate information on the arrival times of the incoming pulses, which can be difficult to achieve due to the aforementioned characteristics of IR-UWB. As shown in [6], [7] timing errors as small as fractions of a nanosecond can seriously degrade the system performance. Synchronization of UWB systems has therefore received considerable attention over the past ten years; an overview of the various strategies is given in [8].

Timing recovery is typically performed in two stages : a coarse synchronization is first carried out to quickly identify the symbol starting frame (acquisition[1] stage); then, a tracking stage aims at refining the initial estimate and maintaining the timing error below the chip duration. Various approaches for UWB signal acquisition can be categorized into two main groups : detection based methods and estimation based methods. The basic principle used in the first group is to perform a correlation between the received waveform and a locally generated template of the transmitted pulse, delayed by a candidate phase (evaluated in a serial, parallel, or hybrid manner), followed by a threshold comparison [9]. The requirement of synthesizing a template waveform for exploiting phase information is typical of *coherent* receivers. In some situations, it may be better to explore the timing uncertainty region following a "look-and-jump" principle rather than linear search [10]. Search space reduction techniques have also been proposed to quickly identify the subset of the search space in which the true phase of the received signal lies [11]. For the estimation based methods, the timing offset is typically obtained by maximizing a statistic over a set of candidate phases. This statistic is usually obtained from correlation of the received signal with a template signal and no threshold comparison is involved. A first way to proceed is to take advantage of the cyclostationarity associated to the frame repetition pattern of impulse radio signaling [12]. A Maximum Likelihood (ML) timing estimator is derived in [14] by considering a rake structure and assuming the pulse waveform to be known at the receiver, which may be unrealistic. The channel impulse response is actually required at the receiver to generate the optimal template. Therefore, some works have been devoted to joint channel estimation and synchronization based on least squares [15] or transform-domain techniques [16]. However, a precise characterization of the channel response may be difficult to achieve due to the large number of paths. Hence, other approaches have been developed with no particular assumption on the received template waveform (this is the fundamental characteristic of any *non-coherent* receiver) : pieces of the received signal (*dirty template*) are used as correlation pattern in [17][19] and in [20] the timing estimation problem is analysed under the unconditional ML criterion. Acquisition can also be performed from energy measurements and a judiciously designed signal structure at the transmitter [21], [22] or by modifying the polarity of the pulses using carefully designed binary codes [23]. The unique features of IR-UWB signals make the energy detection based non-coherent receiver [24] the preferred solution for most applications, as coherent receivers lead to high computational

[1]Two parts are usually distinguished in this process, the frame timing and the symbol timing.

cost.

Most of the synchronizations methods rely on pilot symbols or training sequences to overcome the rich multipath diversity in UWB systems; some of the methods can operate in *blind* mode, in the sense that they do not require any pilot symbol (NonData-Aided, NDA) to work hence enabling a maximization of the effective transmitted throughput and a minimization of the mean transmitted power. The term *blind* can translates into a slightly different problem statement depending on the application objectives. In the field of electronic warfare (EW), blind estimation is a key process for passive listening [26][27], with the objective of detecting various technical characteristics of the observed signal with no prior knowledge. Similar blind techniques are also developed for spectrum sensing in the field of cognitive radio, with the aim of opportunistically providing wireless links that best meet the user communications requirements [25].

A few recent works on blind UWB timing estimation co-authored by the present authors are reviewed in this paper. In a first part of the paper, we focus on the estimation of the chip length of a time-hopping IR-UWB signal from sparse, noisy timing measurements, which is closely related to the estimation of the pulse repetition interval of a radar pulse train [28] from time-of-arrival (ToA) data. We present a novel *round*[2]-based nonlinear cost function combining various incomplete observation sets [29]; thanks to a highly oscillatory behavior of this function, it is shown how the chip duration can be estimated in a blind manner. This approach has the advantage of providing performance bounds for the chip time estimate; however, its main drawback is that it relies on an ideal model for timing data. Hence, the channel characteristics are not really taken into account. So, we then study the problem of joint ToA and chip length estimation owing to an adaptative energy detection window [30]. A first stage of the proposed receiver is devoted to ToA estimation from the energy samples following the maximum selection principle. A second stage then yields the chip duration estimate by iteratively changing the integration window using a bi-dimensional nonlinear cost function. The approach is validated for the IEEE 802.15.4a channel model [31]. These results may contribute to improve the flexibility of UWB receivers, with the possibility to synchronize at any time by observing any time window of the incoming signal. The approach finds application both in EW and in cognitive radio, where some key parameters of the modulation scheme can eventually be adapted to meet changes in spectral masks. In second part of the paper, we turn our attention on an energy detection based NDA algorithm for orthogonal pulse shape modulated (PSM) IR-UWB signals. This modulation scheme has interesting features [32] compared to standard schemes of binary pulse amplitude modulation (BPAM) or binary pulse position modulation (BPPM), but most of the existing acquisition approaches does not apply to it. Thanks to a unique signal structure, it is shown that simple overlap-add operations followed by energy detection enables synchronization [33]. The proposed algorithm remains functional under practical scenarios i.e. in the presence of inter-frame and inter-symbol interference (IFI & ISI) and with M-ary modulation.

[2]Rounding to the nearest integer.

II. Signal Model and Problem Statement

In the present paper, we consider an IR-UWB system transmitting information bearing symbols $d(n)$ with a Time-Hopping (TH) format and either antipodal Pulse Amplitude Modulation (PAM) or Pulse Shape Modulation (PSM). In case of PAM, the transmitted signal can then be expressed as

$$s(t) = \sum_{n} d(n) p_T\left(t - nT_s\right), \qquad (1)$$

the symbol-long waveform $p_T(t)$ taking the form

$$p_T(t) = \sum_{j=0}^{N_f-1} p(t - jT_f - c_jT_c) \qquad (2)$$

where $d(n) \in \{-1, 1\}$, T_f stands for the frame time and $\{c_j\}_{j=0}^{N_f-1} \in [0, N_c - 1]$ represent the time-hopping sequence, the quantification of temporal hops being controlled by the *chip duration* T_c with a total number N_f of frames per symbol; $p(t)$ denotes the elementary pulse (also known as the *monocycle*) of ultrashort duration $T_p < T_c$.

If PSM is employed, the transmitted signal is

$$s(t) = \sum_{n} p_{T,d(n)}\left(t - nT_s\right), \qquad (3)$$

with each information-bearing symbol $d(n) \in \{0, 1, ..., M-1\}$ being conveyed using one particular orthogonal pulse from the set $S = \{p_0(t), ..., p_{M-1}(t)\}$, as

$$p_{T,d(n)} = \sum_{j=0}^{N_f-1} p_{d(n)}(t - jT_f - c_jT_c) \qquad (4)$$

The transmitted signal $s(t)$ propagates through a fading channel which can typically be described by a tapped-delay line model with an impulse response $h(t) = \sum_{l=0}^{L-1} \lambda_l \delta(t - \tau_l)$, where $\{\lambda_l, \tau_l\}_{l=0}^{L-1}$ are channel path gains and delays respectively, with $\tau_l < \tau_{l+1}\ \forall l$. Hence, in case of PAM, the received signal can be written as (a similar expression is obtained for PSM)

$$r(t) = \sum_{n} d(n) p_R\left(t - nT_s - \tau_0\right) + \eta(t) \qquad (5)$$

where $p_R(t)$ stands for the received symbol waveform, i.e. $p_R(t) = p_T(t) \star h(t) = \sum_{l=0}^{L-1} \lambda_l p_T(t - \tau_{l,0})$, $\tau_{l,0} = \tau_l - \tau_0$ being the relative path delay and $\eta(t)$ accounts for both ambient noise and multiple-access interference.

In the sequel, our aim is to estimate the timing offset τ_0 with no prior knowledge on the transmitted symbols nor on the channel state. We also investigate the possibility to achieve timing acquisition in the absence of knowledge of some key parameters of the modulation scheme (T_c, T_f, ...).

III. Timing Acquisition with no prior Knowledge

A. Chip time estimation via modeling of ToA

In this section, the issue of blind timing acquisition of an IR-UWB signal is treated in such a way that no prior knowledge is required. As pointed out in a recent paper [29], this problem can be solved in the same way as pulse repetition interval (PRI) estimation of a radar pulse train from ToA measurements. Many methods have been proposed in the literature on this subject based on histograming, Kalman filtering, Euclidean algorithm, periodogram or function optimization. The standard model which is taken into consideration for a series of sparse and noisy discrete events, arising from a periodical process, relies on a set of random variables $\mathcal{Y} = \{y_j\}_{j=1,2,...,n'}$, being expressed as $y_j = k_j T + \tau_0 + \eta_j$, where $T > 0$ is the unknown period, indices $k_j \in \mathbb{N}^*$ specify the events that have been observed, and the elements η_j characterize the measurement noise[3], here being considered as identically distributed, zero-mean Gaussian random variables with standard deviation σ_η. In case of a IR-UWB, T_c can be recovered from such model once pulses ToA have been collected, through energy measurements and thresholding. Period T then corresponds to the chip time T_c and the coefficients k_j are described through the generic model $k_j = jN_c + c_j$, where c_j are the pseudo-random code elements taking integer values in $[0,\, N_c - 1]$. To better reflect the unknown transmitter parameters and the severe propagation conditions (background noise, multipath), the data set $\mathcal{Y}$ can be modified according to given proportion(s) of outliers or/and missing observations.

In absence of prior knowledge, the problem of timing acquisition can be decomposed in two steps, the first one focusing on the chip time estimation from ToA differences (hence the unknown phase τ_0 is removed), the second one being devoted to the search of the initial time offset (frame/symbol timing). We consider first step as being the main issue in a fully blind approach (for the cases of PAM or PSM modulations), as T_c is a fundamental parameter of the process controlling the position of the pulses in time and other parameters such as T_f or T_s being directly related to T_c (at least for short TH codes). As a result, a "conventionnal" acquisition method based on dirty templates [17] may yield to frame/symbol timing once an estimate of T_c is available. Therefore, we focus only on chip time estimation in this section.

We introduced a novel cost function defined from the set of time data $\boldsymbol{t} = \{t_j\}_{j\in\{1,\,2,\,...,\,n\}}$ resulting from adjacent pair differencing $t_j = y_{j+1} - y_j = (N_c + \Delta c_j)\, T_c + \delta_j$, $j \in \{1,\, 2,\, ...,\, n' - 1\}$; as a result $\delta_j = \eta_{j+1} - \eta_j$ becomes a correlated random variable with distribution $\mathcal{N}\left(0,\, 2\sigma_\eta^2\right)$. Our contribution can be viewed as an extension of a previous work of Sidiropolous *et al.* [35] who investigated the benefits of *round*-based processing of ToA data. Following this principle of quantization, we have shown that some key features of the modulation scheme (chip time, frame time,...) can be revealed from a mixing of $n = n' - 1$ partial functions operating on punctured observation sets; the corresponding cost function takes the form

$$f(\boldsymbol{t}, \widetilde{T}) = \sum_{m=1}^{n} h_m\left(\boldsymbol{t}, \widetilde{T}\right), \tag{6}$$

each partial function h_m being expressed as

$$h_m\left(\boldsymbol{t}, \widetilde{T}\right) = \left| \sum_{j=1, j\neq m}^{n} \frac{t_j}{\widetilde{T}} - \text{round}\left(\sum_{j=1, j\neq m}^{n} \frac{t_j}{\widetilde{T}} \right) \right|. \tag{7}$$

where $\widetilde{T}$ denotes a candidate value of the chip time.

Due to the operations involved, $f(.)$ exhibits pseudo-periodical oscillations, with increasing frequency as the period hypothesis tends towards T_c, which is a local minimum (Fig. 1); an approximate expression of the pseudo-frequency of oscillation is $f_o \simeq nN_c/T_c$.

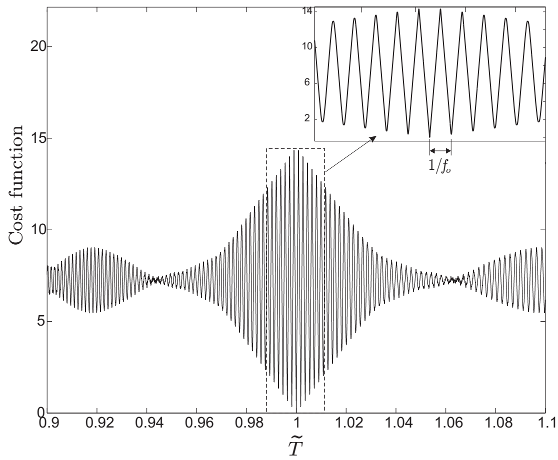

Figure 1. Cost function properties: (a) Evaluation for $T_c = 1$, $n = 30$ and $N_c = 20$.

The procedure proposed for chip time estimation combines multiple hops (MH) controlled by the pseudo-frequency estimate and a Golden Section Search (GSS). Owing to a limited complexity processing, the cost function envelope is precisely evaluated over the search space while avoiding the problem of staying in a particular local minimum. The oscillation pseudo-frequency depends upon the number of observations taken into account; hence, processing many data sets with different lengths n_k lead to various groups of local minima "matching only" in the nearby of T_c (Fig. 2). The proposed algorithm, denoted as Multiple Data Sets - Adjacent (MDS-ADJ), relies on a combination of various minima positions resulting from the processing of multiple data sets.

We proved that this algorithm has a loose performance bound expressed as $\mathbb{E}\left(\left(\hat{T}_c - T_c\right)^2\right) \geqslant B_L \cong \left(2\sigma_\eta^2\right) / \left(n_K N_c\right)^2$, n_K being the longest set of ToA differences used for blind estimation. From Monte-Carlo simulations, we remarked that the proposed MDS-ADJ approach is a good

[3] The percent *jitter*, defined as $(3\sigma_\eta/T_c) \times 100$, is considered in the sequel to reflect the measurement noise.

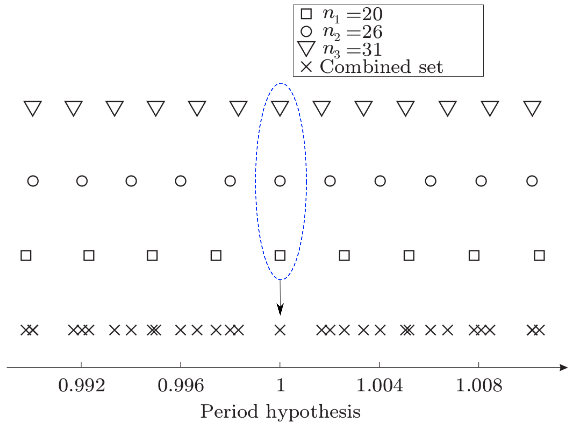

Figure 2. Local minima positions for $T_c = 1$, $N_c = 20$ and various sets of observations having distinct dimensions.

alternative to reference methods such as periodogram [36] or SLS2-ALL [37] (Fig. 3). Its statistical accuracy at low to moderate noise levels is rather close to the Cramér-Rao Bound B_{T_d} (corresponding to ToA differences model), while avoiding both search space sampling and evaluation of trigonometric functions. By diversification of the observed time data, an efficient tradeoff can be achieved between estimation errors and computational complexity. However, the method has the drawback of requiring a relatively restricted search interval (a coarse estimate has to be available first, thanks to the SLS2-ADJ approach [35], for example). Also, no solution for an optimal setting of observation lengths $\boldsymbol{n} = \{n_1, n_2, ..., n_K\}$ is available yet. The sensitivity of MDS-ADJ to outliers is another weak point, which can be slightly mitigated by a proper tuning at the ToA detection stage (increased threshold value to reduce the rate of erroneous data).

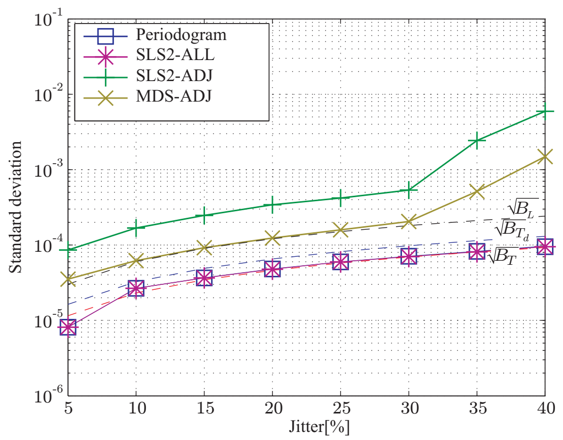

Figure 3. Chip time estimation error against jitter (standard deviation)

B. Joint ToA/chip time estimation

We now investigate the possibility to process jointly ToA/chip time estimation from energy measurements, with no prior knowledge except that the received signal has a time-hopping format of the form

$$s(t) = \sum_{j=-\infty}^{\infty} w_{rx}(t - jT_f - c_jT_c - \zeta_j - \tau_0) + \eta(t), \quad (8)$$

As we operate from the bandpass filtered analog signal at the output of the receiving antenna, we make the distinction between the clock-jitter $\zeta_j \propto \mathcal{N}\left(0,\, \sigma_\zeta^2\right)$and the channel noise $\eta(t) \propto \mathcal{N}\left(0,\, \sigma_\eta^2\right)$. Again, term $\tau_0 \propto \mathcal{U}(0,\, T_f)$ stands for the initial phase reflecting the transmitter-receiver time offset.

If the received signal is applied to a square law device and then integrated over a time window of duration w, energy samples are obtained:

$$z_n = \frac{1}{w}\int_{nw}^{(n+1)w} |s(t)|^2\, dt, \quad n \in \mathbb{N}. \quad (9)$$

A first stage of the proposed scheme is devoted to ToA estimation from the energy samples, following a maximum selection principle. Then, a second stage yields the chip time estimate by iteratively changing the integration window, depending on the values of a nonlinear objective function $f(\widetilde{T}, w)$. The overall structure of the proposed timing scheme is depicted in Fig. 4.

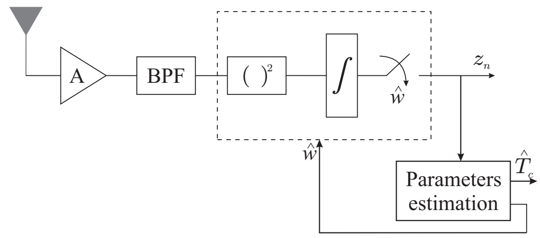

Figure 4. Noncoherent energy detection receiver with adaptive integration window and chip time estimation.

To process the ToA estimation, we first select a reference vector $\mathbf{z}_0 = [z_0,\, z_1,\, ...,\, z_{M-1}]$ of length M which will be used to perform correlation :

$$c_k = \sum_{m=1}^{M} \mathbf{z}_0(m)\mathbf{z}_k(m), \quad (10)$$

$\mathbf{z}_k(m)$ denoting the m-th element of $\mathbf{z}_k = [z_k,\, z_{k+1},\, ...,\, z_{k+M-1}]$ and $n_{max} \geq k + M$ being the total number of collected energy samples.

A maximum value of the temporal spread of the channel is considered, according to the radio environment setup, so that we can choose M and $\mathbf{z}_0$ in such a way that it contains all the energy samples corresponding to first pulse. The relative arrival times $t_j - t_0 = \tau_0 + jT_f + c_jT_c + \zeta_j$ are detected by first identifying a confidence region resulting from a threshold crossing in the energy measurements and then performing local maximum selection after correlation over this region. Then, we get estimates $\{\hat{\theta}_j = t_1^{(j)} - t_1^{(j-1)}\}$ of differential ToA between adjacent pulses, $t_1^{(j)}$ denoting the first energy sample corresponding to j-th pulse. The estimation error is of course directly related to the integration length w; we proposed a bi-dimensional extension of the round-based cost function of Sidiropoulos *et al.* to evaluate this error :

$$f\left(\widetilde{T}, w\right) = \left\| \frac{\hat{\theta}\left(w\right)}{\widetilde{T}} - \text{round}\left(\frac{\hat{\theta}\left(w\right)}{\widetilde{T}}\right) \right\|_1, \qquad (11)$$

where $\hat{\theta}\left(w\right) = \left[\hat{\theta}_j\left(w\right)\right]_{j\in\{2,\ldots,N\}}$ is a vector containing differential ToAs, estimated with an integration window of width w, $\widetilde{T}$ represents the chip duration hypothesis and $\|\cdot\|_1$ stands for ℓ_1 matrix norm.

In the jitter free case, it can be shown that this function vanishes when $\widetilde{T} = T_c$ and $w_r = T_c/r$, $r \in \mathbb{N}$. If jitter is present, error cannot be put to zero anymore, and a certain couple $\left(\hat{T}, \hat{w}\right)$ will minimize (11), considered to be the estimate of (T_c, w_r):

$$\left(\hat{T}, \hat{w}\right) = \text{argmin}_{\widetilde{T}\in\mathcal{D}_{\widetilde{T}},\, w\in\mathcal{D}_w} f\left(\widetilde{T}, w\right) \qquad (12)$$

where $\mathcal{D}_{\widetilde{T}}$ and $\mathcal{D}_w$ denote the search spaces for the chip time and integration length, respectively.

The abovementioned property of $f(.)$ enables a very low computational complexity search procedure (very few values are tested for w) based on iterative one dimensional minimization followed by projection on straight line of equation $y = rw$.

Figure 5 illustrates the results we obtained for 10000 Monte Carlo simulations for CM1 and CM2 channel models (LOS/ NLOS) proposed in the frame of IEEE 802.15.4a. The reference observation $\mathbf{z}_0$ was chosen over a time duration of 300 ns so as to be covering both CM1 and CM2 temporal spreading (hence, to avoid interframe interference), and the considered incertitude time interval for correlation peak search, corresponding to j-th ToA is $t_j + [-T_c/2,\ T_c/2]$. As it can be observed, our approach yields a good chip time estimate for values of jitter below 30%, provided that the SNR is not too low (above−7 dB). Also, the results agree with a theoretical model (not detailed here) that we derived for the differential ToA error resulting from energy detection [30]. Finally, it should be mentionned that the results are strongly related to the number N of received pulses ($N = 30$ in this case).

IV. A Code-Assisted Algorithm for NDA Timing Acquisition of PSM Signals

In this section, we turn our attention on timing acquisition for the special case of orthogonal PSM signals, when no pilot symbols are available (NDA mode). In particular, we give an overview of a recent method relying on an original phase coding scheme enabling a synchronization through simple overlap and add operations followed by energy detection [33].

In the standard M-ary PSM modulation format (see equations 3-4), each information bearing symbol $d(n)$ is conveyed using one pulse from the set $\{p_0(t), p_1(t), \ldots, p_{M-1}(t)\}$. In the proposed approach, we introduce a binary antipodal pulse coding so that the sample mean estimator of the received signal, computed from consecutive symbol long segments, has its energy minimized when the candidate phase equals

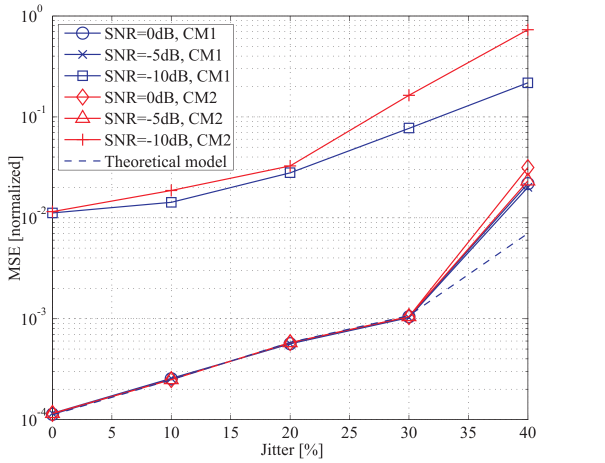

Figure 5. T_c estimation normalized MSE with regard to channel's type and white Gaussian noise ($r = 20$).

the unknown time-offset. With the modified PSM scheme, the symbol-long transmitted waveform takes the following expression ($\lceil . \rceil$ denotes the integer ceil operation) :

$$p_{T,d(n)}(t) = p_0(t - c_0 T_c) + \gamma_n \sum_{j=1}^{N_f - 1} p_{d(n)}(t - jT_f - c_j T_c)$$

where

$$\gamma_n = \sum_m \alpha_n^m \beta_n^m \in \{-1, +1\}, \quad m = 0, 1, \ldots, M-1$$

with

$$\begin{aligned} \beta_n^m &= \beta_{n-1}^m [1 - 2\alpha_n^m] \in \{-1, +1\} \\ \alpha_n^m &= \left[\left\lceil \frac{|d(n) - m| + M}{M} \right\rceil\right]_{mod\, 2} \in \{0, 1\} \end{aligned}$$

As depicted by Fig. 6, two changes have been made : first, each frame starts with an information-free pulse $p_0(t)$; second, pulses with alternate phases are used to represent a particular symbol.

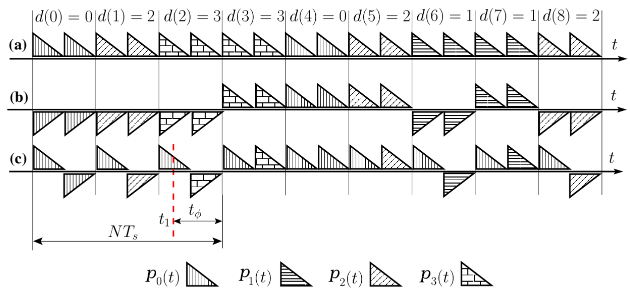

Figure 6. 4-ary PSM signal format with $N_f = 2$; (a) Original modulation scheme (b) Alternate signal inversion (changes in γ_n) (c) Information-free first frame.

The synchronization algorithm relies on computing the sample mean $\overline{x}(t)$ from K segments of the received signal[4]

[4]We assume that the receiver initiates the synchronization process at time t_1.

$x(t) = r(t + t_1)$:

$$\overline{x}(t) = \frac{1}{K} \sum_{k=0}^{K-1} x_k(t)$$

where $x_k(t) = x(t + kT_s)$, $k \in [0, K-1]$, $t \in [0, T_s)$.

In the ISI/IFI free case, it can be shown that the resulting signal is only function of the received waveform associated to information-free pulse $p_0(t)$:

$$\overline{x}(t) = q_0(t - t_\phi) + q_0(t + T_s - t_\phi)$$

where $q_0(t) = \sum_{l=1}^{L-1} \lambda_l p_0(t - \tau_l - \tau_0)$, with $\{\lambda_l, \tau_l\}$ denoting the channel path gains and delays, respectively; t_ϕ denotes the unknown time offset.

As a result, we have the key property that the sample mean takes non-zero values only in the vicinity of t_ϕ. The timing acquisition can then be formulated as a maximisation of an objective function measuring the energy of a delayed version of $\overline{x}(t)$:

$$\hat{t}_\phi = \text{argmax}_{t_\epsilon \in [0,T_s)} J(t_\epsilon)\ ,\ J(t_\epsilon) = \int_0^{T_f} [\overline{x}(t + t_\epsilon)\text{mod}_{T_s}]^2 dt$$

To limit the computational complexity, $J(t_\epsilon)$ may be evaluated over a finite grid of values, at the expense of a reduced synchronization accuracy; in case of frame timing, we can take $t_\epsilon = kT_f$, with integer $k \in [0, N_f)$.

Many Monte Carlo simulations have been carried out to assess the performance of proposed algorithm in terms of normalized mean square error (NMSE), probability of acquisition (PA) and BER against E_x/N_0 (where E_x denotes the energy per pulse). A set of optimized pulses $\{p_i(t)\}_{i=0,1,\ldots,M-1}$ has been used to meet the orthogonality, spectral mask and spectral efficiency requirements [38]; the pulse duration is $T_p = 1.28$ ns. Each symbol consists of $N_f = 10$ frames with $T_f = 12.8$ ns, resulting in symbol duration $T_s = 128$ ns. No TH code has been used as we focused on the single user case. The multipath channel employed in simulations is CM1 indoor channel proposed by IEEE 802.15.3a working group [39] (channel impulse responses were first truncated to avoid IFI/ISI).

The results concerning frame acquisition probability, which is defined as the probability P_A that $|\hat{t}_\phi - t_\phi| \leq T_f$, are illustrated in Fig. 7; a good overall performance can clearly been observed on this figure, as P_A is very close to 1 at $E_x/N_0 = 0$ dB whatever the modulation order is, for $K = 64$. An almost perfect acquisition can still be performed at $E_x/N_0 = -5$ dB for 8-ary modulation. The same approach has also proved to be robust against IFI/ISI over the CM1 channel.

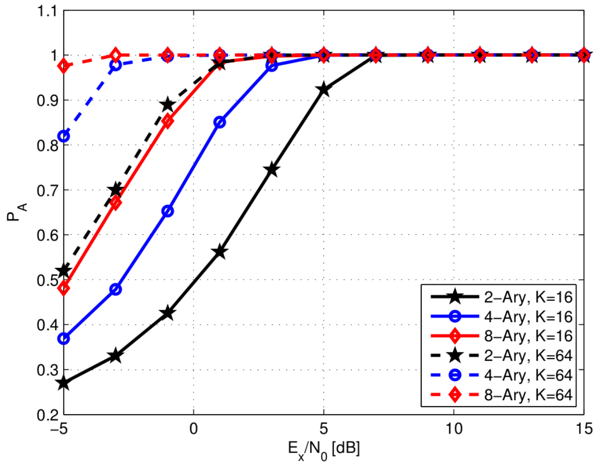

Figure 7. Frame acquisition probability vs. E_x/N_0 in IFI/ISI free case.

V. Conclusions

The issue of blind timing acquisition of IR-UWB signals has been considered in this paper, not only in the sense of NDA mode but also when no prior knowledge is available. In this latter case, it is pointed out that the chip time is a key parameter to estimate to get the unknown time-offset. Two approaches have been overviewed on this subject : the first method relies on a statistical model of the pulse arrival times whereas the second approach jointly estimates ToA and chip duration. Both methods achieve timing through minimization of *round*-based objective functions. A novel NDA acquisition specific to PSM signal format is also described; thanks to an antipodal pulse coding at the transmitter, it is shown that the synchronization can be performed via simple overlapp-add operations and energy detection. This method still performs favorably in presence of IFI/ISI. Various approaches described in this paper may contribute to the development of flexible receivers, able to synchronize at any time despite some changes in the transmitted signal format to best meet spectral mask requirements.

References

[1] H. Arslan, Z. N. Chen, M.-G. Di Benedetto, “Ultra Wideband Wireless Communication,” Wiley-Interscience, Oct. 2006.

[2] A. Willig, “Recent and Emerging Topics in Wireless Industrial Communications: A Selection,” *IEEE Trans. Industrial Informatics*, 4(2): 102-124, 2008.

[3] J. Zhang, P. V. Orlik, Z. Sahinoglu, A. F. Molisch, and P. Kinney, “UWB systems for wireless sensor networks,” *Proceedings of the IEEE*, vol. 97, no. 2, pp. 313–331, 2009.

[4] S. Gezici, Z. Tian, G. B. Giannakis, et al., “Localization via ultra-wideband radios: a look at positioning aspects of future sensor networks,” *IEEE Signal Processing Magazine*, vol. 22, no. 4, pp. 70–84, 2005.

[5] L. Lampe, K. Witrisal, “Challenges and recent advances in IR-UWB system design,”in *Proc. IEEE ISCAS*, pp. 3288-3291, 2010.

[6] W. M. Lovelace and J. K. Townsend, “The effects of timing jitter on the performance of impulse radio,” *IEEE J. Sel. Areas Commun.*, vol. 20, no. 12, pp. 1646–1651, Dec. 2002.

[7] Z. Tian and G. B. Giannakis, “BER sensitivity to mistiming in correlation- based UWB receivers,” *in Proc. IEEE Globecom*, vol. 2, Dec. 2003, pp. 441–445.

[8] S. Aedudodla, S. Vijayakumaran, and T. Wong, “Timing acquisition in ultra-wideband communication systems,” *IEEE Transactions on Vehicular Technology*, vol. 54, no. 5, pp. 1570–1583, Sept. 2005.

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

[10] E. A. Homier and R. A. Scholtz, “Rapid acquisition of ultra-wideband signals in the dense multipath channel,” in Proc. 2002 IEEE Conf. Ultra Wideband Systems Technology, 2002, pp. 105–109.

[11] S. Gezici, E. Fishler, H. Kobayashi, H. Poor, and A. Molisch, “A rapid acquisition technique for impulse radio,” in Proc. 2003 IEEE Pacific Rim Conf. Commun., Comp. and Signal Proc., Aug. 2003, pp. 627–630.

[12] L. Yang, Z. Tian, and G. B. Giannakis, “Non-data aided timing acquisition of ultra-wideband transmissions using cyclostationarity,” *in Proc. 2003 IEEE Intl. Conf. Acoustics, Speech and Signal Proc.*, vol. 4, 2003, pp. 121– 124.

[13] Z. Tian, L. Wu, “Timing Acquisition with Noisy Template for UWB Communications in Dense Multipath,” *EURASIP Journal on Applied Signal Processing*, vol. 2005, no. 3, pp. 439-454, March 2005.

[14] Z. Tian and V. Lottici, “Efficient timing acquisition in dense multipath for UWB communications,” *in Proc. 2003 IEEE Vehicle Technology Conf.*, 2003, pp. 1318–1322.

[15] C. Carbonelli and U. Mengali, “Synchronization algorithms for UWB signals,” *IEEE Trans. Commun.*, vol. 54, no. 2, pp. 329–338, Feb. 2006.

[16] I. Maravic, M. Vetterli, and K. Ramchandran, “Channel estimation and synchronization with sub-nyquist sampling and application to ultra-wideband systems,” *in Proc. 2004 Intl. Symp. Circuits and Systems*, vol. 5, May 2004, pp. 381–384.

[17] L. Yang, G.B. Giannakis, “Timing Ultra-Wideband signals with dirty templates”, *IEEE Trans. Commun.* 53 (11) (2005) 19521963.

[18] L. Yang, G.B. Giannakis, A. Swami, “Noncoherent Ultra-Wideband (de)modulation”, *IEEE Trans. Commun.* 55 (4) (2007) 810819.

[19] S. Farahmand, X. Luo, and G. B. Giannakis "Demodulation and Tracking with Dirty Templates for UWB Impulse Radio: Algorithms and Performance," *IEEE Transactions on Vehicular Technology*, v.54, 2005, p.1595

[20] J. A. Lopez-Salcedo, G. Vazquez, "Waveform-Independent Frame Timing Acquisition for UWB Signals", *IEEE Trans. on Signal Processing*, vol. 55, pp. 279-289, Jan 2007.

[21] X. Luo and G. B. Giannakis, “Low-complexity blind synchronization and demodulation for (ultra-) wideband multi-user ad hoc access,” *IEEE Trans. Wireless Commun.*, vol. 5, no. 2, pp. 1930–1941, Jul. 2006.

[22] Y. Qiao, T. Lv, L. Zhang, “A New Blind Synchronization Algorithm for UWB-IR Systems,” VTC Spring 2009.

[23] Y. Ying, M. Ghogho, A. Swami, “Code-Assisted Synchronization for UWB-IR Systems: Algorithms and Analysis”, *IEEE Transactions on Signal Processing* 56(10-2): 5169-5180 (2008).

[24] K. Witrisal, G. Leus, G. J. M. Janssen, M. Pausini, F. Troesch, T. Zasowski and J. Romme, "Noncoherent Ultra-Wideband Systems," *IEEE Signal Processing Mag.*, vol. 26, no. 4, pp. 48-66, July 2009.

[25] B. Zayen, A. M. Hayar, and D. Nussbaum, “Blind spectrum sensing for cognitive radio based on model selection,” *in Proc. 3rd International Conference on Cognitive Radio Oriented Wireless Networks and Communications CrownCom 2008*, 15–17 May 2008, pp. 1–4.

[26] W. A. Gardner, "Signal interception : a unifying theoretical framework for feature detection," *IEEE Trans. On Communications*, Vol. 36, No. 8, pp. 897-906, 1988.

[27] A. E. Spezio, "Electronic Warfare Systems," *IEEE Trans. Microwave Theory & Techniques*, vol. 50, No. 3, pp. 633-644, Mar. 2002.

[28] B. M. Sadler, S. D. Casey, “On periodic pulse interval analysis with outliers and missing observations”, *IEEE Transactions on Signal Processing* 46(11): 2990-3002 (1998)

[29] M. I. Stanciu, S. Azou, A. Serbanescu, “On the Blind Estimation of Chip Time of Time-Hopping Signals Through Minimization of a Multimodal Cost Function”, *IEEE Trans. on Signal Processing*, 59 (2), pp. 842-847, 2011.

[30] M. I. Stanciu, S. Azou, E. Radoi, A. Serbanescu, “An adaptive energy detection approach for estimating the chip time of an impulse radio signal”, to be submitted to *IET Communications*.

[31] A. Molisch, D. Cassioli, C. C. Chong, S. Emami, A. Fort, B. Kannan, J. Kåredal, J. Kunisch, H. G. Schantz, K. Siwiak, M. Z. Win, ”A comprehensive standardized model for ultrawideband propagation channels,” *IEEE Trans. on Antennas and Propagation*, Vol. 54, No. 11, pp. 3151-3166, 2006.

[32] M. Ghavami, L. B. Michael, S. Haruyama, and R. Kohno, “A novel UWB pulse shape modulation system,” *Wireless Personal Communications*, vol. 23, pp. 105–120, 2002.

[33] R. Akbar, E. Radoi, S. Azou, “Energy detection based blind synchronization for pulse shape modulated IR-UWB systems”, *IEEE 22nd Int. Symp. on Personal, Indoor and Mobile Radio Communications, PIMRC 2011*, Toronto, Canada, September 11-14, 2011.

[34] I. Guvenc, Z. Sahinoglu, and P. Orlik, “TOA estimation for IR-UWB systems with different transceiver types,” *IEEE Trans. on Microwave Theory and Techniques*, 54(4), 1876-1886, 2006.

[35] N. D. Sidiropoulos, A. Swami, B. M. Sadler, "Quasi-ML period estimation from incomplete timing data," *IEEE Trans. on Signal Processing*, Vol. 53, No. 2, pp. 733-739, 2005.

[36] E. Fogel, M. Gavish, "Parameter estimation of quasi-periodic sequences," *Proc. of the Int. Conf. on Acoustics, Speech and Signal Process. (ICASSP)*, vol. 4, pp. 2348-2351, April 1988.

[37] I. V. L. Clarkson, "Approximate maximum-likelihood period estimation from sparse, noisy timing data," *IEEE Trans. Signal Processing*, Vol. 56, No. 5, pp. 1779-1787, May 2008.

[38] M. Matsuo, M. Kamada, and H. Habuchi, “Design of UWB pulses based on B-splines,” *in proc. IEEE Intl. Symp. on Circuits and Systems*, Japan, May 2005, pp. vol. 6, pp. 5425–5428.

[39] J. R. Foerster, M. Pendergrass, and A. F. Molisch, “A channel model for ultra wideband indoor communication,” *in proc. Intl. Symp. on Wireless Pers. Multimedia Commun.*, Japan, Oct. 2003.