Novel Fine Synchronization Using TDT for Ultra Wideband Impulse Radios

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***Abstract*—Ultra-Wideband (UWB) technology for indoor wireless communications has received increasing consideration recently for his potential of high data rates with low-complexity transceivers. Timing synchronization represents a foremost challenge in realizing this potential. In this paper, a novel fine synchronization method has been established. By applying this method, we develop and test timing algorithms in both data-aided (DA) and non-data-aided (NDA) modes. The proposed timing scheme consists of two complementary floors or steps. The first step consists on a coarse synchronization which is founded on the recently proposed acquisition scheme based on dirty templates (TDT). Indeed, this method is characterized by correlating adjacent waveform segments. In the second step, we investigate a new fine synchronization algorithm which gives an improved estimate of timing offset. The simulation results proved performance improvement of our timing synchronization compared to the original TDT algorithm in terms of mean square error.**

Keywords- Time-Hopping (TH); pulse amplitude modulation (PAM); estimation; timing acquisition; synchronization; performance; ultra-wideband (UWB)

I. INTRODUCTION

UWB impulse radios (UWB-IR) have attracted increasing interest due to their potential to propose high user capacity with low-complexity and low-power transceivers [1]. It is approved by the Federal Communications Commission's (FCC) Report in which the UWB spectral mask is released and published in February 2002. Most of these benefits initiate from the distinctive characteristics inherent to UWB wireless transmissions [2]. These make UWB connectivity appropriate for indoor and especially short-range high-rate wireless environments, as well as for strategic outdoor communications. However, to harness these benefits, one of the most critical challenges is the synchronization step and more specifically timing offset estimation. Bit error rate (BER) analysis also exposes evident performance degradation of UWB radios due to mistiming [3]. The complexity of which is accentuated in UWB owing to the fact that information bearing waveforms are impulse-like and have low amplitude. In addition, compared to narrowband systems, the difficulty of timing UWB signals is increased further by the dense multipath channel that remains unknown at the synchronization step. These reasons give explanation why synchronization has obtained so much importance in UWB research [4], [5], [6], [7].

Numerous timing algorithms have been proposed recently for UWB impulse radios. Least squares (LS) [8] and Maximum-likelihood (ML) approaches [9] are available, but tend to be computationally complex as they need high sampling rates. In [10], a blind synchronization algorithm that takes advantage of the shift invariance structure in the frequency domain is proposed. An accurate signal processing model for a Transmit-reference UWB (TR-UWB) system is given in [11]. The model considers the channel correlation coefficients that can be estimated blindly. In [12], the authors proposed a code-assisted blind synchronization (CABS) algorithm which relies on the discriminative nature of both the time hopping code and a well-designed polarity code. Timing with dirty templates (TDT), which is the starting point of this paper, was introduced in [13] for rapid synchronization of UWB signals. This technique is based on correlating adjacent symbol-long segments of the received waveform. TDT is functional with random and unknown transmitted symbol sequences. When training symbols are approachable, the performance of the TDT synchronizer can be improved by approving a data-aided (DA) mode [13]. The DA mode significantly outperforms the non-data-aided (NDA) one. However, the training sequences require an overhead which reduces the bandwidth and energy efficiency.

In this paper, we adopt first a blind (or coarse) synchronization technique, which is Timing with dirty templates (TDT). Its principle is to correlate two consecutive symbol-long segments of the received waveform. In particular, synchronization will be asserted when the correlation function reaches its maximum. This allows TDT algorithms to effectively collect the multipath energy even when the spreading codes and the channel are both unknown. However, this technique estimates coarsely (or roughly) the value of timing offset, therefore not precisely, and this may cause a shortfall in performance of our UWB impulse radio systems. To improve the synchronization performance of the original TDT, our contribution will be to implement a new fine synchronization step and insert it after the coarse one, which is original TDT. The principle of our fine synchronization algorithm is to make a fine search to find the exact moment of pulse beginning (fine estimation of timing offset). This is achieved by correlating two consecutive symbol-long segments of the received waveform but this time in an interval that corresponds to the number of frames included in one data symbol. Compared with the original TDT synchronizers, this new structure improves greatly the system energy efficiency. Simulation results show that this new synchronizer using TDT can realize a lower mean square error (MSE) than the original TDT in both non-data-aided (NDA) and data-aided (DA) modes.

The rest of this paper is organized as follows. Section II describes our system model. Section III outlines the TDT algorithm of [13] in a single-user links and upper bounds on the mean square error of TDT estimators in both non-data-aided (NDA) and data-aided (DA) modes are derived. In Section IV, we introduced our novel fine synchronization. In Section V, simulations are carried out to corroborate our analysis. Conclusions are given in Section VI.

II. SYSTEM MODEL FOR SINGLE-USER LINKS

In UWB impulse radios, each information symbol is transmitted over a T_s period that consists of N_f frames [1]. During each frame of duration T_f, a data-modulated ultra-short pulse p(t) with duration $T_p \ll T_f$ is transmitted from the antenna source. The transmitted signal is

$$v(t) = \sqrt{\varepsilon}\sum_{k=0}^{+\infty} \tilde{s}(k) \sum_{i=0}^{N_f-1} p(t - iT_f - c_{th}(i)T_c - kT_s) \quad (1)$$

where ε is the energy per pulse. $\tilde{s}(k) \coloneqq s(k)\tilde{s}(k-1)$ are differentially encoded symbols and drawn equiprobably from a finite alphabet. In our case, s(k) are denoting the binary PAM information symbols. User separation is realized with pseudo-random TH-codes $c_{th}(i)$, which time-shift the pulse positions at multiples of the chip duration T_c [1]. In this paper, we focus on a single user link and treat multi-user interference (MUI) as noise.

The transmitted signal propagates through the multipath channel with impulse response

$$g(t) = \sum_{l=0}^{L-1} \alpha_l \delta(t - \tau_l) \quad (2)$$

where $\{\alpha_l\}_{l=0}^{L-1}$ and $\{\tau_l\}_{l=0}^{L-1}$ are amplitudes and delays of the L multipath elements, respectively. The channel is assumed quasi-static and among $\{\tau_l\}_{l=0}^{L-1}$, τ_0 represents the propagation delay of the channel.

Then, the received waveform is given by

$$r(t) = \sqrt{\varepsilon}\sum_{k=0}^{+\infty} \tilde{s}(k) p_T\left(t - kT_s - \tau_{l,0} - \tau_0\right) + \eta(t) \quad (3)$$

where $\tau_{l,0}$ is arbitrary reference at the receiver representing the delay relative to the arrival moment of the first pulse, $\eta(t)$ is the additive noise and $p_T(t)$ denotes the received symbol waveform as

$$p_T(t) = \sum_{i=0}^{N_f-1} p(t - iT_f - c_{th}(i)T_c) * g(t + \tau_0) \quad (4)$$

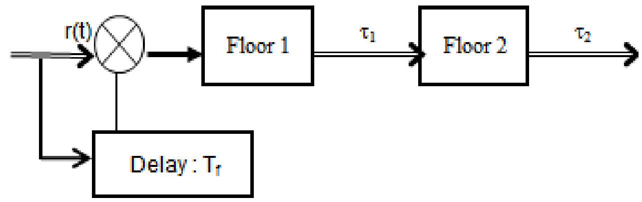

Figure 1. Block diagram of our synchronization scheme

where * indicates the convolution operation. We define the timing offset as $\Delta\tau \coloneqq \tau_{l,0} - \tau_0$. Let us suppose that $\Delta\tau$ is in the range of $[0, T_s)$ and we will show in the rest of this paper that this assumption will not affect the timing synchronization.

In the next two sections, we will develop a low-complexity fine synchronization approach using TDT synchronizer in order to find the desired timing offset. The block diagram of our synchronization scheme is shown in Fig.1. Our approach will be evaluated in both non-data-aided (NDA) and data-aided (DA) modes, without knowledge of the multipath channel and the transmitted sequence.

III. TDT APPROACH

As mentioned previously, our proposed timing scheme consists of two complementary floors or steps. The first is based on a coarse (or blind) synchronization that is timing with dirty templates (TDT) developed in [13]. In this section, we will give an outline of the TDT approach to better understand the overall timing synchronization suggested in this paper. The general structure description of our system model with first stage synchronization (TDT) is illustrated in Fig.2.

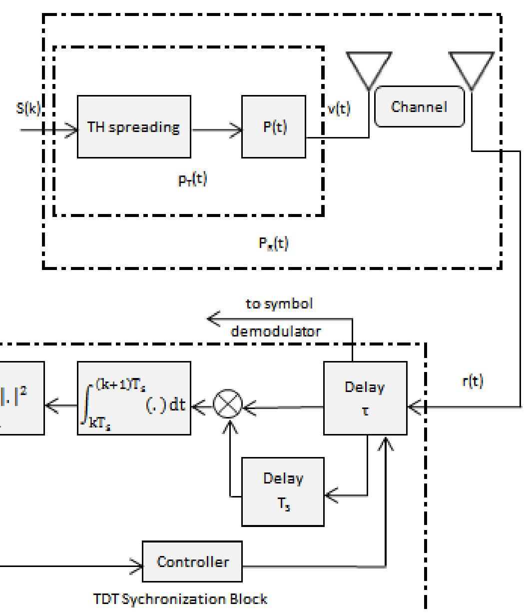

Figure 2. Description of our model with first stage synchronization

The basic idea behind TDT is to find the maximum of square correlation between pairs of successive symbol-long segments. These symbol-long segments are called "dirty templates" because: i) they are noisy, ii) they are distorted by the unknown channel, and iii) they are subject to the unknown offset τ_0. Then, we will analyze $\widetilde{\tau_0}$ representing estimate offset of τ_0 by deriving upper bounds on their mean square error (MSE) in both non-data-aided (NDA) and data-aided (DA) modes.

For notational brevity and after setting $p_T(t) := p_R(t-\tau_{l,0})$, the received waveform simplifies to

$$r(t) = \sqrt{\varepsilon}\sum_{k=0}^{+\infty} \tilde{s}(k) p_R(t - kT_s - \tau_0) + \eta(t) \qquad (5)$$

Thereafter, a correlation between the two adjacent symbol-long segments $r(t + kT_s)$ and $r(t + (k-1)T_s)$ is achieved. Let $x(k;\tau)$ the value of this correlation $\forall k \in [1, +\infty)$ and $\tau \in [0, T_s)$,

$$x(k;\tau) = \int_0^{T_s} r(t + kT_s + \tau)\, r(t + (k-1)T_s + \tau) dt \qquad (6)$$

Applying the Cauchy-Schwartz inequality and substituting the expressions of $r(t + kT_s)$ and $r(t + (k-1)T_s)$ to (6), $x(k;\tau)$ becomes

$$x(k;\tau) = \tilde{s}(k-1)[\, \tilde{s}(k-2)\, \varepsilon_A(\widetilde{\tau_0}) + \tilde{s}(k)\, \varepsilon_B(\widetilde{\tau_0})] + \zeta(k;\tau) \qquad (7)$$

where $\varepsilon_A(\tau) := \varepsilon \int_{T_s-\tau}^{T_s} p_R^2(t)dt$, $\varepsilon_B(\tau) := \varepsilon \int_0^{T_s-\tau} p_R^2(t)dt$, and $\zeta(k;\tau)$ corresponds to the superposition of three noise terms [13] and can be approximated as an additive white Gaussian noise (AWGN) with zero mean and σ_ζ power.

By exploiting the statistical properties of the signal and noise, the mean square of the samples in (7) is given by

$$E\{x^2(k;\tau)\} = \frac{1}{2}[\varepsilon_A(\widetilde{\tau_0}) + \varepsilon_B(\widetilde{\tau_0})]^2 + \frac{1}{2}[\varepsilon_A(\widetilde{\tau_0}) - \varepsilon_B(\widetilde{\tau_0})]^2 + \sigma_\zeta^2 \qquad (8)$$

We notice that $\varepsilon_B(\widetilde{\tau_0}) + \varepsilon_A(\widetilde{\tau_0}) = \varepsilon\int_0^{T_s} p_R^2(t)dt := \varepsilon_R$ for $\widetilde{\tau_0} \in [0, T_s)$, where ε_R represents the constant energy corresponding to the unknown aggregate template at the receiver. Then the mean square of $x^2(k;\tau)$ can be rewritten as follows,

$$E\{x^2(k;\tau)\} = \frac{1}{2}(\varepsilon_R)^2 + \frac{1}{2}[2\varepsilon_A(\widetilde{\tau_0}) - \varepsilon_R]^2 + \sigma_\zeta^2 \qquad (9)$$

Since the term $\varepsilon_A(\widetilde{\tau_0})$ reaches its unique maximum at $\widetilde{\tau_0} = 0$, then $E\{x^2(k;\tau)\}$ also reached its unique maximum at $\widetilde{\tau_0} = 0$. Thus, an estimate of timing offset τ_0 is given by

$$\hat{\tau}_0 = \arg max_{\tau\in[0,T_s]} E\{x^2(k;\tau)\} \qquad (10)$$

In the practice, the mean square of $x^2(k;\tau)$ is estimated from the average of different values $x^2(k;\tau)$ for k ranging from 0 to M – 1 obtained during an observation interval of duration MT_s. In what follows, we summarize the TDT algorithm in its NDA form and then in its DA form.

A. *Non-Data-Aided (Blind) Mode*

For the synchronization mode NDA, the synchronization algorithm is defined as follows:

$$\hat{\tau}_{0,\,nda} = \arg max_{\tau\in[0,T_s]} E\,\{x^2(k;\tau)\}$$

$$x_{nda}(M;\tau) = \frac{1}{M}\sum_{m=0}^{M-1}\left(\int_{mT_s}^{(m+1)T_s} r(t+\tau)r(t+\tau+T_s)dt\right)^2 \qquad (11)$$

By using (7), the expression of $x_{nda}(M;\tau)$ can be rewritten as follows

$$x_{nda}(M;\tau) = \frac{1}{M}\sum_{m=0}^{M-1}[s(m-1)s(m-2)\varepsilon_A(\widetilde{\tau_0}) + s(m)s(m-1)\varepsilon_B(\widetilde{\tau_0}) + \zeta(m;\tau)]^2 \qquad (12)$$

From (9) and (10), the estimation of delay τ_0 is made possible due to the presence of the term $\varepsilon_A(\widetilde{\tau_0}) - \varepsilon_B(\widetilde{\tau_0})$. Unfortunately for the estimator $x_{nda}(M;\tau)$, this term exists only if the transmitted sequence presents an alternating sign between the symbols $s(m-2)$ and $s(m)$. Thus, for the synchronization in NDA mode, the performances of this approach are affected by the sign of the transmitted symbols. To increase the chances that the estimator $x_{nda}(M;\tau)$ is expressed as a function of the energy difference, an increase in the observation interval length is required. However, such an increase leads to increased acquisition delays. Where does the idea of using the data-aided (DA) approach.

B. *Data-Aided Mode*

The number of samples M required for reliable estimation can be reduced noticeably if a data-aided (DA) approach is pursued [14]. The delays can be significantly reduced through the use of training sequences with alternating sign between the symbols $s(m-2)$ and $s(m)$, i.e. $s(m-2) = -s(m)$. This observation suggest that the training sequence $\{s(k)\}$ for DA TDT mode follows the following alternation $[1,1,-1,-1]$ (this by working with a M-ary PAM symbol); i.e.

$$s(k) = (-1)^{\lfloor \frac{k}{2} \rfloor} \qquad (13)$$

This pattern is particularly attractive, since it simplifies the algorithm proposed by the TDT approach, for the DA mode, to become:

$$\hat{\tau}_{0,\,da} = \arg max_{\tau\in[0,T_s]}\{x_{da}(M;\tau)\}$$

$$x_{da}(M;\tau) = \left(\int_0^{T_s} r(t+\tau)r(t+\tau+T_s)dt\right)^2 \qquad (14)$$

with $r(t) = \frac{2}{M}\sum_{k=0}^{\frac{M}{2}-1}(-1)^k r(t + 2kT_s + \tau)$.

The estimator in (14) is essentially the same as (12), except that training symbols are used in (14). However, theses training symbols are instrumental in improving the estimation performance. This is approved by the simulation results in Section V.

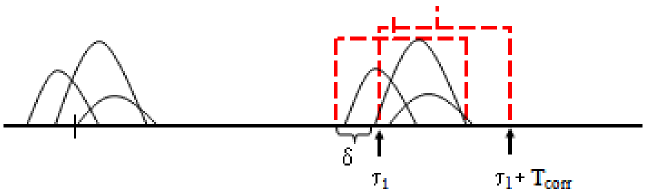

Figure 3. Principle of second synchonization floor

IV. PROPOSED FINE SYNCHRONIZATION

In this section, we present the second floor or step of our synchronization approach. This second floor achieves a fine estimation of the frame beginning, after a coarse research in the first. The concept which is based this floor is extremely simple. The idea is to scan the interval $[\tau_1 - T_{corr},\ \tau_1 + T_{corr}]$ with a step noted δ by making integration between the received signal and its replica shifted by T_f on a window of width T_{corr}. τ_1 being the estimate delay deducted after the first synchronization floor and the width integration window value's T_{corr} will be given in Section V. This principle is illustrated in Fig.3. We can write the integration window output for the n^{th} step $n\delta$ as follows:

$$Z_n = \sum_{k=0}^{K-1} \left| \int_{\tau_1+n\delta}^{\tau_1+n\delta+T_s} r(t - kT_s) r(t-(k+1)T_s) dt \right| \quad (15)$$

where $n = -N+1..0..N-1$, $N = \lfloor T_{corr}/\delta \rfloor$ and K is number of frames considered for improving the decision taken at the first floor. The value of n which maximizes Z_n provides the exact moment of pulse beginning that we note $\tau_2 = \tau_1 + n_{opt}\delta$. Thus, the fine synchronization is performed. Finally, note that this approach will be applied in both non-data-aided (NDA) and data-aided (DA) modes. We will see later (Section V) in what mode this approach gives better result compared to those given by the original approach TDT.

V. SIMULATION RESULTS

In this section, we will evaluate the performance of our proposed fine synchronization approach with simulations. The UWB pulse is the second derivative of the Gaussian function with unit energy and duration $T_p \approx 0.8\text{ns}$. Simulations are achieved in the IEEE 802.15.3a channel model CM1 [15]. The sampling frequency chosen in the simulations is f_c = 50 GHz. Each symbol contains N_f = 32 frames each with duration T_f = 35 ns. We used a random TH code uniformly distributed over $[0, N_c - 1]$, with N_c = 35 and T_c = 1.0 ns. The width integration window value's T_{corr} is 4 ns. The performance of our synchronization approach is tested for various values of M.

In Fig. 4, we first test the mean square error (MSE) of NDA and DA TDT algorithms summarized in Section III. The MSE is normalized by the square of the symbol duration T_s^2, and plotted versus signal-to-noise rate (SNR). From the simulation results obtained from Fig.4, we note that increasing the duration of the observation interval M leads to improved performance for both NDA and DA modes. We also note that the use of training sequences (DA mode) leads to improved performance compared to the NDA mode.

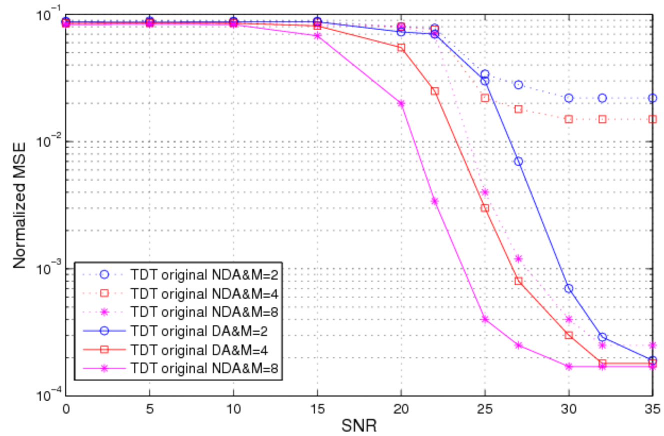

Figure 4. Normalized MSE of the original TDT synchronizer in both NDA and DA modes

In Figs. 5-7, we evaluate and compare by simulation the performance (in term of MSE) of our proposed fine synchronizer with the original NDA and DA TDT algorithms in [13]. For purposes of these simulations, we kept the same channel model and the same TH code parameters as those used previously in Fig. 4. In Fig. 5, we compare the performances of the new fine synchronization approach in both NDA and DA modes. In Fig. 6-7, we compare the performances of both original TDT and fine synchronization approach proposed in both NDA and DA modes for different values of M. In comparison with the original TDT approach, we note that the new approach outperforms the NDA mode and offers a slight improvement in DA mode. Even without any training symbol sequence, our synchronizer can greatly outperform the original NDA TDT especially when M is small. This performance improvement is enabled at the price of fine synchronization approach introduced in second floor which can further improve the timing offset found in first floor (coarse synchronization approach : TDT) .

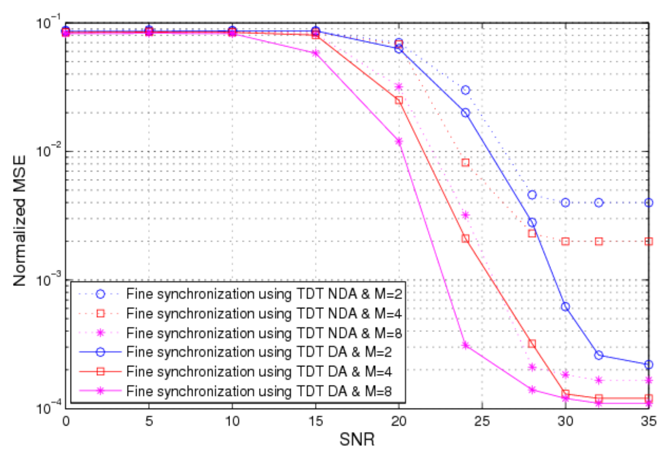

Figure 5. Normalized MSE of our fine synchronization approach in both NDA and DA modes

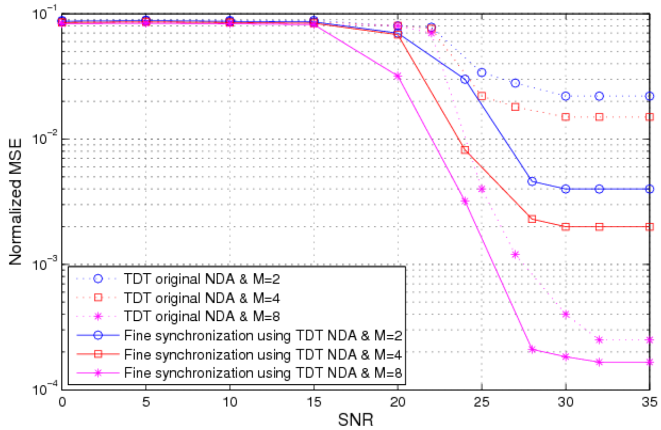

Figure 6. Performances comparison between original TDT and our fine synchronization approaches in NDA mode

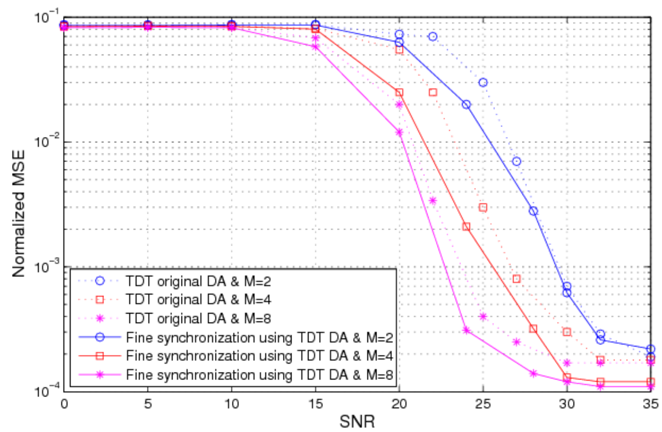

Figure 7. Performances comparison between original TDT and our fine synchronization approaches in DA mode

VI. CONCLUSIONS

In this paper, we propose a novel fine synchronization scheme using TDT algorithm for UWB radio system in single-user links. With the fine synchronization algorithm introduced in second floor after the TDT (first floor), we can achieve a fine estimation of the frame beginning. The simulation results show that even without training symbols, our new synchronizer can enable a better performance than the original TDT in NDA mode especially when M is small and offers a slight improvement in DA mode.

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