FINE SYNCHRONIZATION WITH UWB TH-PAM SIGNALS IN AD-HOC MULTI-USER ENVIRONMENTS

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***Abstract*—To synchronize Ultra-Wideband (UWB) signals with pulse amplitude modulation (PAM) and time hopping (TH) spreading in ad-hoc multi-user environments, we propose in this paper to develop and test a novel fine synchronization algorithm in both data-aided (DA) and non-data-aided (NDA) modes. The proposed synchronization scheme is decomposed into two successive floors or steps. The first floor consists on a coarse synchronization which is based on timing with dirty templates (TDT) acquisition scheme. In the second floor, we consider a new fine algorithm which provides an ameliorated estimate of timing offset. Simulation results and comparisons are also presented to confirm our theoretical analysis and performance improvement (in terms of mean square error) compared to the original TDT algorithm in multi-user environments.**

***Keywords-* UWB, pulse amplitude modulation (PAM), synchronization, performance, multi-user**

I. INTRODUCTION

Currently, the most important discussion subject in UWB ad-hoc impulse radios is how to obtain the best possible synchronization and more specifically an efficient timing offset estimation. The synchronization complexity is accentuated in UWB systems compared to other's due to the fact that waveforms are impulse-like and have low amplitude. Furthermore, the difficulty of timing UWB signals is provoked by the dense multipath channel unknown at the synchronization step. These reasons explain why synchronization has taken so much importance in UWB literature (see e.g., [1]-[7]). An algorithm has grown substantially in recent years is timing with dirty templates (TDT) introduced in [8] and developed for UWB signals.

In this paper, we develop a novel fine synchronization algorithm for UWB TH-PAM signals. To ameliorate the synchronization performance, our contribution is to realize a fine synchronization floor and insert it after the coarse one (which is TDT). The principle is to make a fine search for the exact moment of pulse beginning (timing offset) by correlating two consecutive symbol-long segments of the received waveform in an interval that corresponds to the frames number included in one data symbol. Simulations and comparisons show that our synchronizer improves the corresponding system performance in terms of mean square error (MSE) compared to the original TDT.

The rest of this paper is organized as follows. Section 2 describes the UWB TH-PAM system in multi-user environments. Section 3 outlines first the TDT algorithm and upper bounds on the mean square error are derived in both non-data-aided (NDA) and data-aided (DA) modes. Then, we presented our novel fine synchronization. In Section 4, simulation results are carried out to corroborate our analysis. Conclusions are given in Section 5.

II. SYSTEM MODEL FOR MULTI-USER LINKS

The UWB time hopping impulse radio signal considered in this paper is a stream of narrow pulses, which are shifted in amplitude modulated (PAM). The same modulated pulse is repeated N_f times (frames number) over a T_s period (symbol time). During each duration frame T_f, a data-modulated ultra-short pulse p(t), with duration $T_p \ll T_f$, is transmitted. The transmitted waveform from the *u*th user is

$$v_u(t) = \sqrt{\varepsilon_u} \sum_{k=0}^{+\infty} s_u(k) p_{u,T}(t - kT_s) \tag{1}$$

where ε_u represents the energy per pulse, $s_u(k)$ are differentially encoded symbols and drawn equiprobably from finite alphabet. In our case, $s_u(k)$ symbolize the binary PAM information symbols and $p_{u,T}(t)$ indicates the transmitted symbol

$$p_{u,T}(t) := \sum_{i=0}^{N_f-1} p(t - iT_f - c_u(i)T_c) \tag{2}$$

where T_c is the chip duration and $c_u(i)$ is the user-specific pseudo-random TH code during the *i*th frame.

The transmitted signal propagates through the multipath channel corresponding to each user. The UWB channel is modeled as tapped-delay line with L_u taps, where $\{\alpha_{u,l}\}_{l=0}^{L_u-1}$ and $\{\tau_{u,l}\}_{l=0}^{L_u-1}$ is amplitude and delay of the L multipath elements, respectively. The channel is assumed quasi-static and among $\{\tau_{u,l}\}_{l=0}^{L_u-1}$, τ_0 represents the propagation delay of the channel. Thus, the received waveform from all users is:

$$r(t) = \sum_{u=0}^{N_u-1} \sqrt{\varepsilon_u} \sum_{l=0}^{L_u-1} \alpha_{u,l} v_u\left(t - \tau_{u,l} - \tau_u\right) + \eta(t) \quad (3)$$

where N_u is the users number, τ_u is the propagation delay of the uth user's direct path and $\eta(t)$ is the zero-mean additive Gaussian noise (AGN). The global received symbol-long waveform is therefore given by

$$p_{u,R}(t) := \sum_{l=0}^{L_u-1} \alpha_{u,l} p_{u,T}(t - \tau_{u,l}) \quad (4)$$

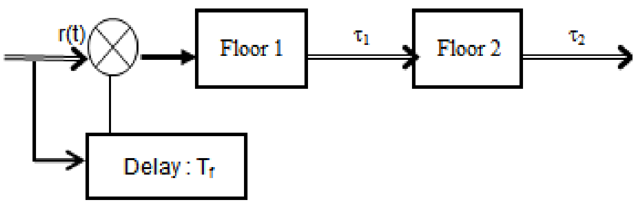

Figure 1. Block diagram of our synchronization scheme

Assuming that the nonzero support of waveform $p_{u,R}(t)$ is upper bounded by the symbol time T_s, the received waveform in (3) can be rewritten as

$$r(t) = \sum_{u=0}^{N_u-1} \sqrt{\varepsilon_u} \sum_{k=0}^{+\infty} s_u(k) p_{u,R}(t - kT_s - \tau_u) + \eta(t) \quad (5)$$

In the next step, we will develop a low-complexity fine synchronization algorithm using original TDT approach and system model described in this section, in order to find the desired timing offset. It will be evaluated in both non-data-aided (NDA) and data-aided (DA) modes.

III. FINE SYNCHRONIZATION ALGORITHM FOR MULTI-USER UWB TH-PAM IMPULSE RADIOS

As cited previously, our proposed synchronization scheme consists of two complementary floors. The first is based on coarse synchronization approach that is TDT developed in [8]. The second consists of a novel fine synchronization algorithm which more improves the timing offset found in the first floor. The structure of our timing scheme is shown in Fig.1. We will first outline the TDT approach for multi-user UWB TH-PAM impulse radios to better understand the whole synchronization scheme suggested in this paper.

A. *Multi-user TDT for UWB TH-PAM impulse radios*

The basic idea behind TDT is to find the maximum of square correlation between pairs of successive symbol-long segments. The description of our system model with first stage synchronization (TDT) is given in Fig.2. First, we analyze $\tilde{\tau}_0$ representing the estimate offset of τ_0 with deriving upper bounds on their mean square error (MSE) in both NDA and DA modes.

For multi-user UWB TH-PAM systems, 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 $\tau \in [0, T_s)$,

$$x(k;\tau) = \sum_{u=0}^{N_u-1} \int_0^{T_s} r(t - kT_s) r(t-(k-1)T_s)\, dt \quad (6)$$

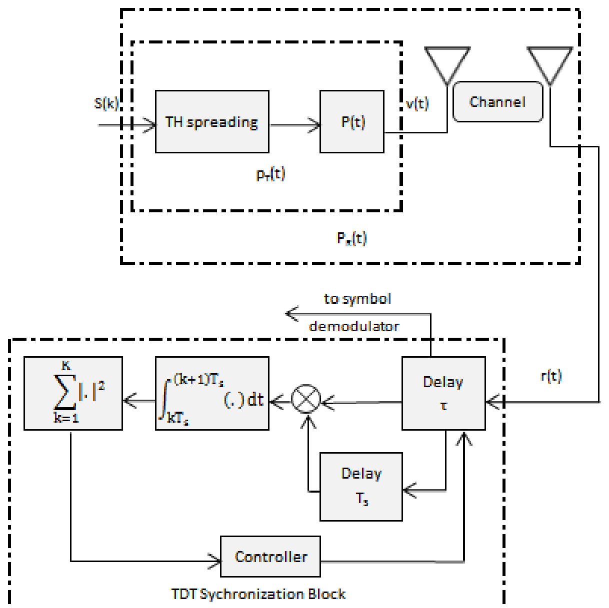

Figure 2. Description of our model with first stage synchronization

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

$$x(k;\tau) = \sum_{u=0}^{N_u-1} s_u(k-1)\left[s_u(k-2)\varepsilon_{u,A}(\tilde{\tau}_u) + s_u(k)\varepsilon_{u,B}(\tilde{\tau}_u)\right] + \xi(k;\tau) \quad (7)$$

where $\varepsilon_{u,A}(\tilde{\tau}_u) := \varepsilon_u \int_{T_s-\tilde{\tau}_u}^{T_s} p_{u,R}^2(t)dt$, $\varepsilon_{u,B}(\tilde{\tau}_u) := \varepsilon_u \int_0^{T_s-\tilde{\tau}_u} p_{u,R}^2(t)dt$, $\tilde{\tau}_u := [\tau_u - \tau]_{T_s}$ and $\zeta(k;\tau)$ corresponds to the superposition of three noise terms [8] and can be approximated as an additive white Gaussian noise (AWGN) with zero mean and σ_ξ power. As mentioned in [8], the noise-free part of the desired user's samples at the correlator output complies with

$$\chi_0(k;\tau) = \varepsilon_{0,A}(\tilde{\tau}_0) - \varepsilon_{0,B}(\tilde{\tau}_0) \quad (8)$$

Substituting the above equation into (7), we find

$$x(k;\tau) = \chi_0(k;\tau) + \sum_{u\neq 0} s_u(k-1)\left[s_u(k)\varepsilon_{u,B}(\tilde{\tau}_u) + s_u(k-2)\varepsilon_{u,A}(\tilde{\tau}_u)\right] + \xi(k;\tau) \quad (9)$$

where $s_u(k)$'s are zero-mean information symbols emitted by the $(u \neq 0)$ th user. If we calculate the average (without squaring), we obtain $E\{x(k;\tau)\} = \varepsilon_{0,B}(\tilde{\tau}_0) - \varepsilon_{0,A}(\tilde{\tau}_0)$ since

$E\{\chi_u(k;\tau)\} = 0$ [8]. 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 MT_s. In what follows, we summarize the TDT algorithm for multi-user UWB TH-PAM impulse radios in its NDA form and then in its DA form.

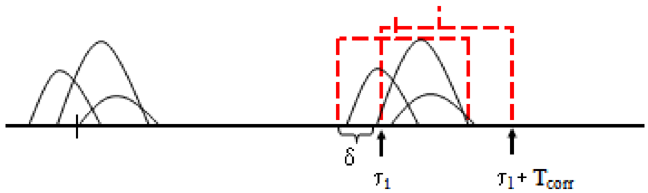

Figure 3. Principle of second synchonization floor

1) Non-Data-Aided-Mode

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

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

$$x_{nda}(M;\tau_u) = \frac{1}{M}\sum_{m=0}^{M-1}\left(x(k;\tau)\right)^2 \qquad (10)$$

The estimator can be verified to be m.s.s consistent by deriving the mean and variance of $x_{nda}(M;\tau_u)$. It has been demonstrated that the single-user TDT estimator is operational even in a multi-user environment [8].

2) Data-Aided-Mode

The samples number M necessary for trustworthy estimation can be clearly reduced if a DA approach is pursued. The delays can be considerably reduced with using training sequences with alternating sign between the symbols s(m-2) and s(m). This observation propose that the training sequences {s(k)} for DA TDT mode follow the following alternation [1,1,-1,-1]; i.e.

$$s(k) = (-1)^{\left\lfloor \frac{k}{2} \right\rfloor} \qquad (11)$$

This pattern is particularly attractive, since it simplifies the proposed algorithm to become in the DA mode:

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

$$x_{da}(M;\tau) = \left(\int_0^{T_s} r(t+\tau)r(t+\tau+kT_s)dt\right)^2 \qquad (12)$$

with $E\left\{(-1)^{\left\lfloor \frac{k}{2} \right\rfloor} r(t+\tau+kT_s)\right\} = \sqrt{\varepsilon}\left[p_{0,R}(t+T_s-\tilde{\tau}_0) + (-1)^k p_{0,R}(t-\tilde{\tau}_0)\right]$ which signifies that the single-user TDT estimator can also be functional in a multi-user scenario.

B. *Fine synchronization algorithm proposed*

In this part, we present the second floor or step of our synchronization approach in multi-user UWB TH-PAM systems. This second floor realizes a fine estimation of the frame beginning, after a coarse research in the first (TDT approach). The concept which is based this floor is really straightforward. 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 removed after the first synchronization floor. This principle is illustrated in Fig.3. We can write the integration window output for the n^{th} step nδ as follows

$$Z_n = \sum_{k=0}^{K-1}\left|\int_{\tau_1+n\delta}^{\tau_1+n\delta+T_s} r(t-kT_s)r(t-(k+1)T_s)dt\right| \qquad (13)$$

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 $\tau_2 = \tau_1 + n_{opt}\delta$. Therefore, the fine synchronization is performed. Finally, we note that this approach will be applied in both NDA and DA modes. We will see later (Section 4) in what mode this approach gives better result compared to those given by the original approach TDT.

IV. SIMULATION RESULTS

In this section, we will evaluate the performance of our proposed fine synchronization approach for UWB TH-PAM signals in ad-hoc multi-user environments. The UWB pulse is the second derivative of the Gaussian function with unit energy and duration $T_p \approx 0.8$ns. Simulations are achieved in the IEEE 802.15.3a channel model CM1 [9]. 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 is tested for various values of M.

In Fig. 4, we first test the mean square error (MSE) corresponding to (10) and (12) in the presence of two interfering users. The two interfering users are asynchronous relative to the desired user. 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.

In Figs. 5-7, we evaluate the performance of our proposed fine synchronizer compared to the original TDT algorithm. For purposes of these simulations, we kept the same simulation parameters as those used previously in Fig. 4. In Fig. 5, we compare the new fine synchronization approach performances 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.

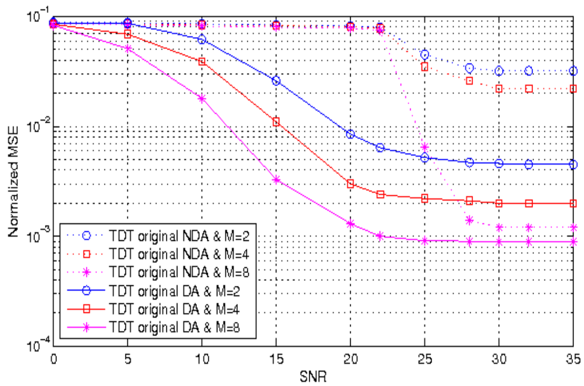

Figure 4. Normalized MSE of multi-user original TDT synchronizer

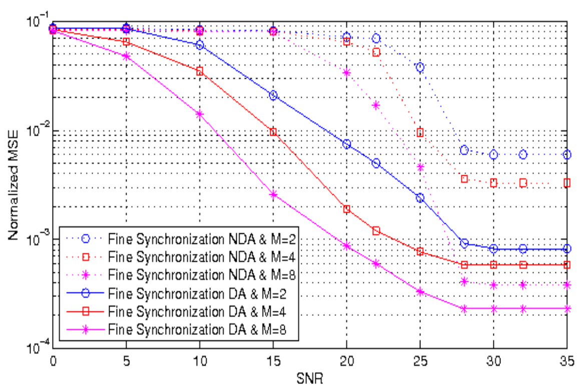

Figure 5. Normalized MSE of our multi-user fine synchronization

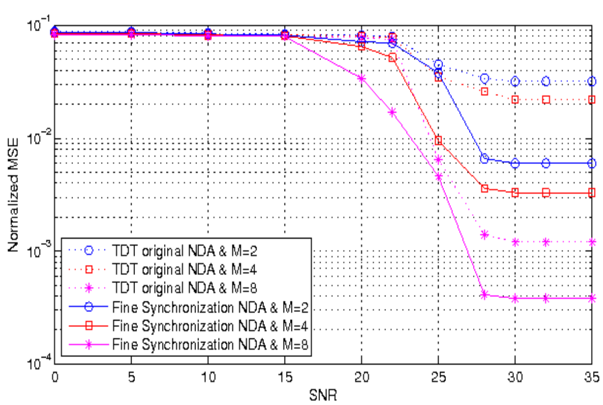

Figure 6. Performances comparison in NDA mode

V. 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.

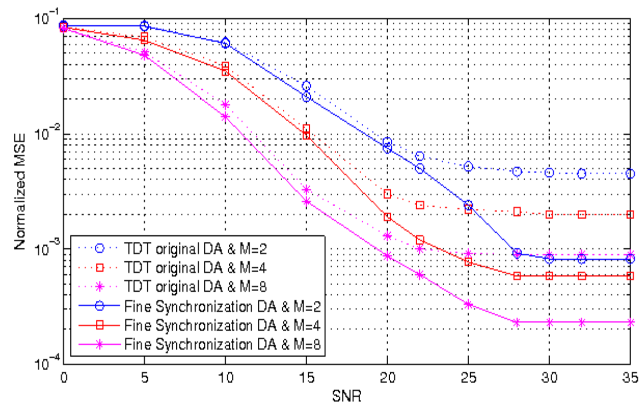

Figure 7. Performances comparison in DA mode

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