Original Research Article

Timing synchronization of ultra-wideband systems using delay line combination receivers

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Abstract: This paper proposes a novel non-data aided timing synchronization algorithm designated as ”timing with delay line combination” (TDLC), to improve the synchronization speed of differential impulse radio ultra-wideband systems. Continuously integrating the combinative output signal provided by the proposed ”frame-differential delay line” (FDL), it is found that the integration output exhibits a sharp rising or falling transition at the moment that the first signal per symbol arrives. By accurately detecting the time of the rising or falling edge, the symbol boundary can be simply derived. The proposed scheme achieves timing synchronization within a single symbol duration.

Keywords: Synchronization; Timing acquisition; Differential transmitted reference (DTR); Impulse radio (IR); Ultra-wideband (UWB)

1. Introduction

UNE of the critical challenges in designing UWB receivers is the synchronization issue. In most instances, the channel information is not known exactly during the synchronization phase. It has been shown that differential transmitted reference (DTR) receivers[1] can resolve the problem of energy collection without any channel information. In a similar approach to that adopted in the DTR receivers, ”timing with dirty templates” (TDT) algorithms employ symbol-long segments of the received signals as ”templates” in the correlation operation[2]. The synchronization criterion of TDT algorithms exploits the fact that the cross-correlation of these ”dirty templates” exhibits a unique maximum at the correct symbol time. However, although TDT algorithms are blind in the sense that they do not require TH code, they are inoperable in multi-user environments in which other users employ the same training pattern.

This paper proposes a novel non-data aided (NDA) synchronization algorithm designated as the ”timing with delay line combination” (TDLC) algorithm. In contrast to TDT algorithms, which rely on acquiring a maximum integration output by testing all of the candidate time offsets (τ), the synchronization criterion of the TDLC algorithm is based on detecting the sharpest rising or falling edge of the continuous integration output of the combinative output signal provided by the frame-differential delay line (FDL) during one symbol period. The TDT algorithm requires $2K \times N_i$ symbol periods for each round, where K is the number of pairs of symbollong received segments required for reliable estimation and N_i is the number of candidate time offsets. However, the. proposed TDLC algorithm requires just one symbol period per round. Therefore, the TDLC algorithm is superior to the TDT algorithms in terms of its synchronization speed. The present simulation results also demonstrate that the TDLC algorithm achieves a higher probability of detection (PD) than the TDT algorithms in both multipath and multi-user environments.

2. Signal model

The transmitted signal from the *k*th user is given by

$$s_k(t) = \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_f-1} (d_{k,i})^j w(t - iT_s - jT_f - c_{k,j}T_c), \tag{1}$$

where *k* is the user index; *i* is the symbol index; *j* is the frame index; $d_{k,i} \in \{+1,-1\}$ is the data sequence for the *k*th active user; *w*(t) is the transmitted pulse waveform; T_s is the symbol duration; T_f is the pulse repetition time; $\{c_{k,j}\}_{j=0}^{f-1N}$ is the time hopping (TH) code; and T_c is the chip duration. Each symbol is transmitted in N_f successive frames with one pulse per frame and the *j*th transmitted pulse of the *i*th symbol is modulated by $(d_{k,i})^j$.

As discussed in[3], let $D_{k,p}$ indicate the time offset between the *p*th and the *(p+1)*th transmitted pulses from the *k*th user, where *Dk,p = Tf* +(*ck,mod*(*p*+1,*Nf*)−*ck,mod*(*p,Nf*))×*Tc* for *p* ∈ [0,N_f − 1]. Eq. (1) can then be rewritten as

$$s_k(t) = \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_f-1} (d_{k,i})^j w(t - iT_s - c_{k,0}T_c - \sum_{p=0}^{j-1} D_{k,p}),$$

where $\sum_{p=0}^{-1} D_{k,p} = 0$ is defined.

The multipath channel corresponding to each user *k* is modeled as a tap delay line with L_k taps, whose amplitudes $\{\alpha_{k,l}\}_{l=1}^{L_k}$ and delays $\{\tau_{k,l}\}_{l=1}^{L_k}$ are invariant over one symbol duration. The channel impulse response is given by

$$h_k(t) = \sum_{l=1}^{L_k} \alpha_{k,l} \delta(t - \tau_{k,l}), \tag{3}$$

where $\tau_{k,}^{1}$ is the propagation delay of the first arrival signal.

The aggregated waveform for all of active users has the form

$$\begin{aligned} r(t) &= \sum_{k=0}^{N_u-1} s_k(t) * h_k(t) + n(t) \\ &= \sum_{k=0}^{N_u-1} \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_f-1} \sum_{l=1}^{L_k} (d_{k,i})^j \alpha_{k,l} w(t - iT_s - c_{k,0}T_c \\ &\quad - \sum_{p=0}^{j-1} D_{k,p} - \tau_{k,l}) + n(t) \end{aligned}$$

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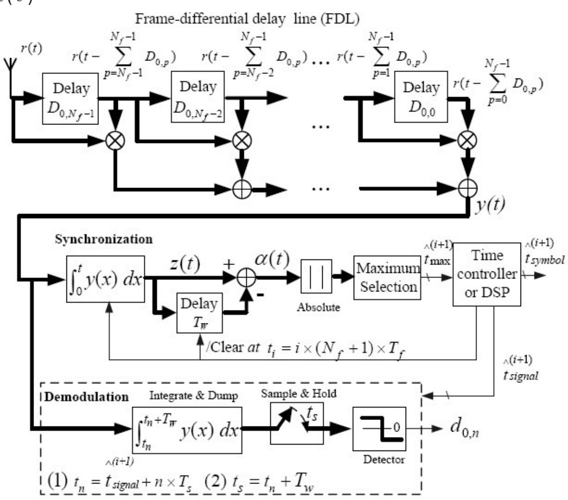

Figure 1. Block diagram of DLC receiver for the *0*th user.

$$= \sum_{k=0}^{N_u-1} \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_f-1} v_{k,i,j}(t) + n(t), \tag{4}$$

where N_u is the total number of active users; *n(t)* is the additive Gaussian noise, and $v_{k,i,j}(t) = (d_{k,i})^j \sum_{l=1}^{L_k} \alpha_{k,l} w(t - iT_s -$ variant over one symbol duration, $v_{k,i,j}(t) = (d_{k,i})^j v_{k,i,}{}^0(t - c_{k,0}T_c - \sum_{p=0}^{j-1} D_{k,p} - \tau_{k,l})$. Since $\{\alpha_{k,l}\}_{l=1}^{L_k}$ and $\{\tau_{k,l}\}_{l=1}^{L_k}$ are in- $\sum_{p=0}^{j-1} D_{k,p})$. Eq. (4) can be rewritten as

$$r(t) = \sum_{k=0}^{N_u-1} \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_f-1} (d_{k,i})^j v_{k,i,0}(t - \sum_{p=0}^{j-1} D_{k,p}) + n(t). \tag{5}$$

3. Timing with delay line combination (tdlc) algorithm

The delay line combination (DLC) receiver proposed in this study is derived from the differential IR-UWB system presented in [4]. However, in the current DLC receiver, the delay elements are arranged in a cascade rather than in parallel. This sequence of delay elements is designated as the "frame-differential delay line" (FDL). The delays in the FDL are denoted by $D_{k,Nf}-1, D_{k,Nf}-2, ..., D_{k,}{}^0$, sequentially[5].

As shown in Fig. 1, the active user is indexed as *0*, and *y(t)* is the combinative output signal of the N_f tap branches of the FDL. The continuous integration output of *y(t)* is given by

$$\begin{aligned} z(t) &= \int_0^t y(x)dx \\ &= \sum_{m=0}^{N_f-1} \int_0^t r(x - \sum_{p=m}^{N_f-1} D_{0,p}) \times r(x - \sum_{p=m+1}^{N_f-1} D_{0,p})dx, \end{aligned} \tag{6}$$

where $\sum_{p=N_f}^{N_f-1} D_{0,p} = 0$ is defined.

The DLC receiver introduces a delay time T_w. Note that the value of T_w should be designed appropriately in order to optimize the performance of the proposed synchronization algorithm [6]. Generally, it is reasonable to assume $T_w \leq T_{mds}^{(k)}$, where $T_{mds}^{(k)} = \tau_{k,L_k} - \tau_{k,1}$ is the maximum delay spread under the channel impulse response $h_k(t)$. Subtracting $z(t - T_w)$ from z(t) gives

$$\begin{aligned} \alpha(t) &= z(t) - z(t - T_w) \\ &= \sum_{m=0}^{N_f-1} \int_{t-T_w}^t r(x - \sum_{p=m}^{N_f-1} D_{0,p}) \times r(x - \sum_{p=m+1}^{N_f-1} D_{0,p})dx. \end{aligned} \tag{7}$$

Substituting Eq. (5) into Eq. (7), yields

$$\begin{aligned} \alpha(t) = \sum_{m=0}^{N_f-1} \int_{t-T_w}^t &\{ \sum_{k_1=0}^{N_u-1} \sum_{i_1=-\infty}^{\infty} \sum_{j_1=0}^{N_f-1} (d_{k_1,i1})^{j_1} v_{k_1,i_1,0}(x \\ &- \sum_{p=0}^{j_1-1} D_{k_1,p} - \sum_{p=m}^{N_f-1} D_{0,p}) + n(x - \sum_{p=m}^{N_f-1} D_{0,p})\} \\ &\times \{ \sum_{k_2=0}^{N_u-1} \sum_{i_2=-\infty}^{\infty} \sum_{j_2=0}^{N_f-1} (d_{k_2,i2})^{j_2} v_{k_2,i_2,0}(x - \sum_{p=0}^{j_2-1} D_{k_2,p} \\ &- \sum_{p=m+1}^{N_f-1} D_{0,p}) + n(x - \sum_{p=m+1}^{N_f-1} D_{0,p})\}dx. \end{aligned} \tag{8}$$

Extracting the desired terms with indexes $k^1 = k^2 = 0$, $i^1 = i^2$, $j^1 = m$, and $j^2 = m + 1$ from Eq. (8) gives

$$\alpha(t) = \sum_{m=0}^{N_f-1} \sum_{i=-\infty}^{\infty} \int_{t-T_w}^{t} (d_{0,i})^m v_{0,i,0}(x - \sum_{p=0}^{m-1} D_{0,p} - \sum_{p=m}^{N_f-1} D_{0,p})$$
$$\times (d_{0,i})^{m+1} v_{0,i,0}(x - \sum_{p=0}^{m} D_{0,p} - \sum_{p=m+1}^{N_f-1} D_{0,p}) dx + \Psi(t) \quad (9)$$
$$= (N_f) \sum_{i=-\infty}^{\infty} (d_{0,i}) \int_{t-T_w}^{t} v_{0,i,0}^2 (x - T_s) dx + \Psi(t),$$

where $\Psi(t)$ denotes the noise and interference terms[7]. If $\Psi(t)$ is ignored, $|\alpha(t)|$ exhibits a local maximum when $^{t} - T_w = (i + 1)T_s + \tau^{0\,1}_{,} + c^{0\,0}_{,} T_c$ for each symbol index i. Therefore, the true symbol boundary, i.e. $t_{symbol}^{(i+1)} = (i+1)T_s + \tau_{0,1}$, can be determined by detecting the time at which $|\alpha(t)|$ exhibits its local maximum during each symbol period.

Assuming that the time at which $|\alpha(t)|$ exhibits its local maximum is denoted by $\widehat{t}_{max}^{(i+1)}$ and is estimated in accordance

with the criterion[8]

$$\widehat{t}_{max}^{(i+1)} = \arg \max_{t_i < t \leq t_{i+1}} (|\alpha(t)|), \quad (10)$$

where $t_i = i \times (N_f + 1) T_f$, then the estimated arrival time of the first signal in the $(i+1)$th symbol $\widehat{t}_{signal}^{(i+1)}$ can be derived by

$$\widehat{t}_{signal}^{(i+1)} = \widehat{t}_{max}^{(i+1)} - T_w. \quad (11)$$

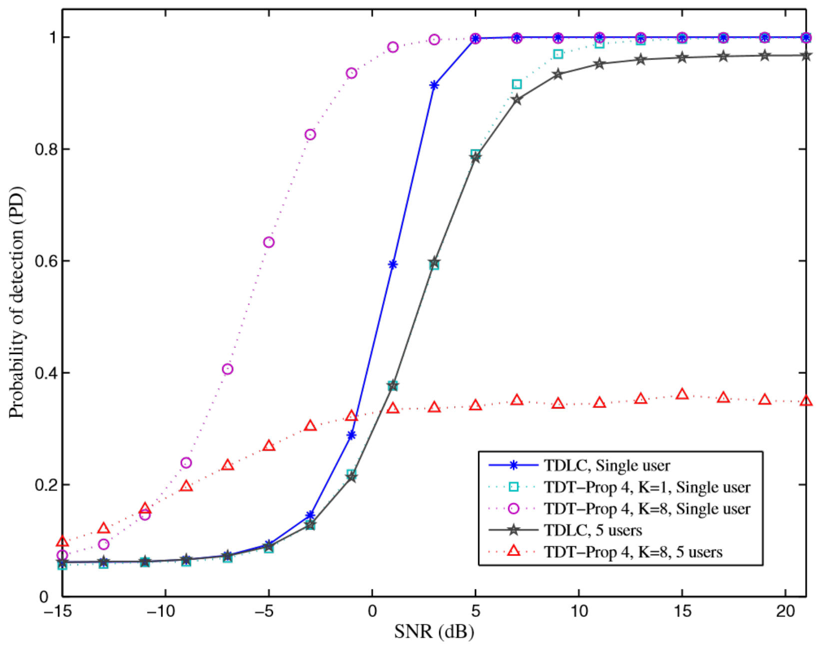

Figure 2. Probability of detection (PD) with frame-level coarse timing synchronization.

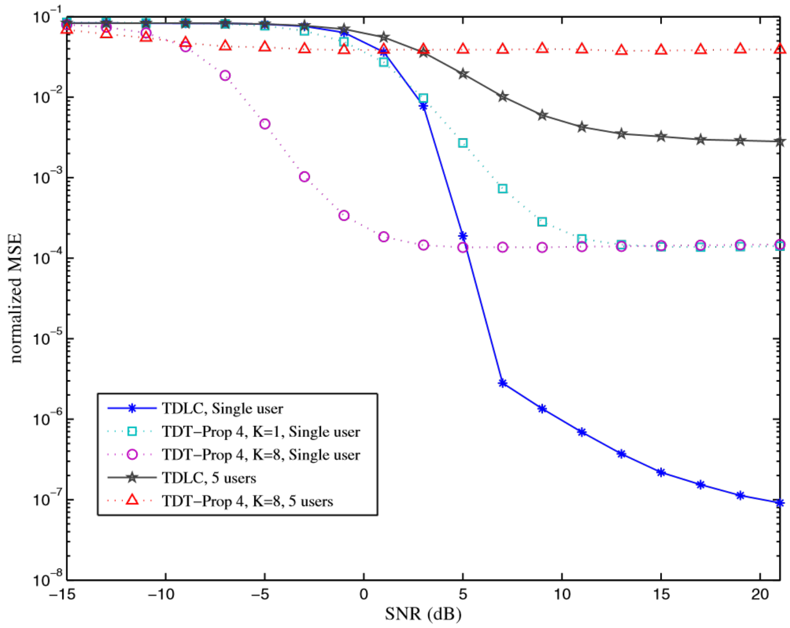

Figure 3. Normalized MSE (Note that MSE is normalized with respect to T_s^2).

Finally, the estimated symbol boundary $\hat{t}^{(i+1)}_{symbol}$ can be obtained from

$$\hat{t}^{(i+1)}_{symbol} = \hat{t}^{(i+1)}_{signal} - c_{0,0}T_c. \tag{12}$$

It should be noted here that the proposed algorithm is inoperable for some specific TH patterns, for example $D^0_{,p} = D^0_{,q}$ for each $p \neq q$. Therefore, the TH code $\{c_{0,j}\}_{j=0}^{N_f-1}$ must be constrained to satisfy $D_{0,p} \neq D_{0,q}$ for some $p \neq q$ in order to rule out this particular case [9]. Furthermore, the polarity change of the first pulse of the following symbol must be consistent with that of any pulse of the current symbol to ensure that the synchronization algorithm obtains an optimal performance.

4. Simulation results

A series of simulations are performed to evaluate the performance of the proposed TDLC algorithm. The multipath channels are generated using the UWB channel model proposed by IEEE 802.15.3a, with parameters $(1/\Lambda, 1/\lambda, \Gamma, \gamma)$ = (42.9,0.4,7.1,4.3) ns. The channel impulse response is assumed to be invariant over one symbol duration. For each user *k*, assuming the propagation delay of the first arrival signal $\tau_{k,}^{1}$ is uniformly distributed over $[0,T_s)$ ns, with $T_s = N_f \times T_f$. The frame duration is specified as T_f = 35 ns, and each symbol contains N_f = 32 frames. For the desired user (indexed as 0), a TH code $\{c_{0,j}\}_{j=0}^{N_f-1}$ which satisfies $D_{0,p} \neq D_{0,q}$ for each $p \neq q$ is selected. The remaining users are assigned random TH codes uniformly distributed over $[0,N_c)$ with N_c = 35 and T_c = 1 ns. The training sequence for the DA TDT comprises a repeated pattern (1, 1, -1, -1) for all users. For the TDLC algorithm, the transmitted data sequence, $d^0_{,i}$, is randomly generated. Finally, the delay time, T_w, is set to 16 ns in all simulations of the TDLC algorithm.

Figures 2 and **3** show the simulation results obtained by the TDLC algorithm and the TDT algorithms for the probability of detection (PD) and the normalized mean square error (MSE), respectively. It can be seen that the TDLC algorithm outperforms the TDT algorithms. This result is reasonable since the DLC receiver uses the unique time interval between two successive pulses, $D_{k,p}$, as the time delay to correlate the received signal with the time-delayed signal. Therefore, it is more robust to noise and interference than the DT receiver.

The simulation results show that the TDLC algorithm provides a better performance than TDT algorithms with smaller values of *K*, for instance *K*=1, in both multipath and multi-user environments[10].

5. Conclusions

This paper has proposed a novel non-data aided (NDA) timing synchronization algorithm designated as the ”timing with delay line combination” (TDLC) algorithm. The TDLC algorithm can detect the correct symbol boundary within one symbol duration. Furthermore, the synchronization speed of the TDLC algorithm is $2K \times Ni$ times faster than that of the TDT algorithms. The simulation results have shown that the TDLC algorithm achieves a higher probability of detection (PD) and a lower normalized mean square error (MSE) than TDT algorithms in both multipath and multi-user environments.

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