A Joint Channel Estimation and Synchronization Algorithm for High Speed Digital IR-UWB System

Liang Wu and Zaichen Zhang, *Member, IEEE*

***Abstract*—This letter proposes a joint channel estimation and synchronization algorithm for impulse radio ultra-wideband (IR-UWB) communication. High-speed sampling and 1-bit quantization at the receiver are assumed to achieve high data rate with reasonable complexity. Simulation results show that the proposed algorithm works well when inter-symbol interference (ISI) is ignored during the preamble period.**

***Index Terms*—IR-UWB, synchronization, channel estimation, 1-bit quantization.**

I. Introduction

Ultra wideband (UWB) with the advantages of high-speed and low power consumption has been paid much attention [1],[2]. This letter focuses on impulse radio (IR) UWB system, transceiver of which is simple compared to the orthogonal frequency division multiplexing (OFDM) UWB systems. A lot of work has been done on the synchronization and channel estimation of IR-UWB [3-6]. In this letter, we propose a joint channel estimation and synchronization (JCES) algorithm for high-speed sampling and 1-bit quantization IR-UWB system.

UWB signal has a very large bandwidth. According to the Nyquist sampling theorem, there needs an ultra fast analog to digital converter (ADC), which is somehow difficult to realize. In addition the quantization precision is high. So, the receiver of the UWB system must deal with the sampling data with high quantization. In this letter, we proposed the 1-bit quantization UWB system, and it is easy to be implemented, which includes the following two aspects: a comparator implementing the function of traditional ADC, with serial-to-parallel converter, to realize the high speed sampling; the low quantization precision reducing the computational burdens of receiver.

This letter is organized as follows: Section II introduces the signal model, the proposed JCES algorithm is presented in Section III, Section IV gives the simulation result and Section V concludes this letter.

II. Signal Model

The proposed JCES algorithm is data-aided algorithm. Bipolar pulse modulation is assumed. A preamble is added prior to each data block, and the preamble consists of two parts, $p_1(t)$ and $p_2(t,\boldsymbol{u})$, given by

$$p_1(t) = \sum_{n=0}^{N_{p1}-1} (-1)^n p(t-nT_p) \tag{1}$$

where N_{p1} is the number of pulses of $p_1(t)$; the pulse waveform $p(t)$ has time duration T_w. T_p is the time interval between the pulses of $p_1(t)$.

$p_2(t,\boldsymbol{u})$ is for the synchronization of the data block, given by

$$p_2(t,\boldsymbol{u}) = \sum_{n=0}^{N_{p2}-1} u[n]\cdot p(t-nT_p) \tag{2}$$

where N_{p2} is the length of synchronization sequence; $u[n] = \pm 1$ $(n = 0, 1, \ldots, N_{p2}-1)$, is the data payload synchronization sequence. Each block of data can be expressed as

$$x(t,\boldsymbol{a}) = \sum_{n=0}^{N-1} a_n\cdot p(t-nT_d) \tag{3}$$

where $\boldsymbol{a} = \{a_0, a_1, \ldots, a_{N-2}, a_{N-1}\}$ is the data payload, with $a_n \in \{+1,-1\}$; T_d is the time interval between the pulses when the payload is transmitted, and $T_d = T_p/Y$ (Y is a positive integer).

Then a block of the transmitted signal takes the form

$$s(t,\boldsymbol{u},\boldsymbol{a}) = p_1(t) + p_2(t-T_1,\boldsymbol{u}) + x(t-T_1-T_2,\boldsymbol{a}) \tag{4}$$

where T_1 and T_2 denote durations of $p_1(t)$ and $p_2(t,\boldsymbol{u})$, respectively.

The signal $s(t,\boldsymbol{u},\boldsymbol{a})$ is transmitted over a multi-path fading channel with impulse response $h(t)$ which is modeled as a tapped-delay line with L taps [7],[8]. $q(t)$ is the channel response to $p(t)$ and takes the form

$$q(t) = \sum_{j=0}^{L-1} \gamma_j p(t-\tau_j) \tag{5}$$

where γ_j and τ_j are the gain and time delay associated with the j-th path, and satisfying $\tau_0 = 0$ and $\tau_j < \tau_{j+1}$. The channel is assumed to be quasi-static. The received signal is given by

$$\begin{aligned} r(t) &= s(t,\boldsymbol{u},\boldsymbol{a}) \otimes h(t-\tau) + n(t) \\ &= v(t-\tau) + l(t-T_1-\tau,\boldsymbol{u},\boldsymbol{a}) + n(t) \end{aligned} \tag{6}$$

where τ is the propagation delay. $n(t)$ is an additive white Gaussian noise (AWGN) with zero mean and two sided power spectral density $N_0/2$, $v(t)$ is given by

$$\begin{aligned} v(t) &= p_1(t) \otimes h(t) \\ &= \sum_{n=0}^{N_{p1}-1} (-1)^n q(t-nT_p) \end{aligned} \tag{7}$$

Manuscript received July 7, 2010. The associate editor coordinating the review of this letter and approving it for publication was G. Ginis.

This work is supported by NSFC projects (60802005 and 60902010), 863 projects (2007AA01Z2b1 and 2009AA012000), National Science & Technology major project of China (2009ZX03006-008-02), and the NSF of Jiangsu project (BK2009266).

The authors are with the National Mobile Communications Research Laboratory, Southeast University, Nanjing 210096, China (e-mail: {wuliang, zczhang}@seu.edu.cn).

Digital Object Identifier 10.1109/LCOMM.2010.091010.101195

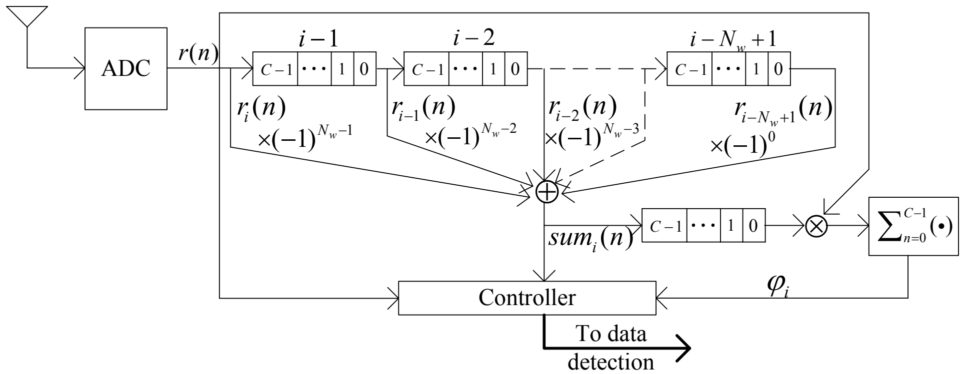

Fig. 1. Block diagram of the proposed JCES algorithm.

used for the synchronization and channel estimation. $l(t,\boldsymbol{u},\boldsymbol{a})$ is given by

$$l(t,\boldsymbol{u},\boldsymbol{a}) = (p_2(t,\boldsymbol{u}) + x(t-T_2,\boldsymbol{a})) \otimes h(t) \tag{8}$$

To avoid the inter-symbol interference (ISI), T_p is assumed to satisfy

$$T_p > T_w + \tau_{L-1} \tag{9}$$

III. The Proposed JCES Algorithm

Fig. 1 shows the block diagram of the proposed JCES algorithm. The sampling interval of "ADC" is T_s and $C = T_p/T_s$ is an integer. The sampled received signal is $r(nT_s)$. For simplicity, let $r(n) = r(nT_s)$, by omitting T_s.

Defining

$$N := \lfloor \tau/T_p \rfloor; \qquad \kappa := \tau - NT_p \tag{10}$$

where $\lfloor\cdot\rfloor$ stands for integer floor operation, one obtains

$$q_\kappa(t) = q(t-\kappa) \tag{11}$$

To grasp the gist of the proposed channel estimation and synchronization algorithm, we consider the noise-free system.

In the i-th T_p time, the received signal can be written as

$$r_i(n) = r(n + i\cdot C) \quad n = 0,1,\cdots,C-1 \tag{12}$$

where $i \in [0,+\propto)$, and i is an integer, and

$$r_i(n) = \begin{cases} 0, & i < N \\ q_\kappa(n), & i = N \\ \begin{matrix}(-1)^{i-N-1}q_{\kappa-T_p}(n) \\ +(-1)^{i-N}q_\kappa(n)\end{matrix}, & i > N \end{cases} \tag{13}$$

As illustrated in Fig.1, the storage depth of sum-window is $C\cdot N_w$. The receiver divides the sum window into N_w parts. Each part is multiplied by "+1" and "-1" alternatively, and then summed. Defining

$$sum_i(n) = \frac{1}{N_w}\sum_{k=i-N_w+1}^{i}(-1)^{k-i+N_w-1}r_k(n) \tag{14}$$

and $sum_i(n)$ is refreshed once every T_p time, one obtains

$$\varphi_i = \sum_{n=0}^{C-1} sum_i(n) r_{i+1}(n) \tag{15}$$

When $i \in [N, N+N_w)$,

$$\begin{aligned} sum_i(n) &= \frac{1}{N_w}\sum_{k=N}^{i}(-1)^{k-i+N_w-1}r_k(n) \\ &= \frac{i-N}{N_w}(-1)^{i-N+N_w}q_{\kappa-T_p}(n) \\ &\quad + \frac{i-N+1}{N_w}(-1)^{i-N+N_w-1}q_\kappa(n) \end{aligned} \tag{16}$$

and

$$\begin{aligned} \varphi_i &= \sum_{n=0}^{C-1} sum_i(n) r_{i+1}(n) \\ &= \sum_{n=0}^{C-1}(-1)^{N_w}[\frac{i-N}{N_w}q_{\kappa-T_p}(n)^2 + \frac{i-N+1}{N_w}q_\kappa(n)^2] \\ &= (-1)^{N_w}\sum_{n=0}^{C-1}[\frac{i-N}{N_w}q_{\kappa-T_p}(n)^2 + \frac{i-N+1}{N_w}q_\kappa(n)^2] \end{aligned} \tag{17}$$

And, when $i \in [N+N_w, N+N_{p1})$,

$$\begin{aligned} sum_i(n) &= \frac{1}{N_w}\sum_{k=i-N_w+1}^{i}(-1)^{k-i+N_w-1}r_k(n) \\ &= (-1)^{i-N+N_w}q_{\kappa-T_p}(n) + (-1)^{i-N+N_w-1}q_\kappa(n) \end{aligned} \tag{18}$$

and

$$\begin{aligned} \varphi_i &= \sum_{n=0}^{C-1} sum_i(n) r_{i+1}(n) \\ &= \sum_{n=0}^{C-1}(-1)^{N_w}[q_{\kappa-T_p}(n)^2 + q_\kappa(n)^2] \\ &= (-1)^{N_w}\sum_{n=0}^{C-1}[q_{\kappa-T_p}(n)^2 + q_\kappa(n)^2] \end{aligned} \tag{19}$$

It can be seen from (17), (19), sign bit of φ_i does not change.

The proposed JCES algorithm can be realized by the following stages:

1) The quantitative precision is 1 bit, so the maximum value of $|sum(n)|$ is not bigger than 1. When the maximum value of

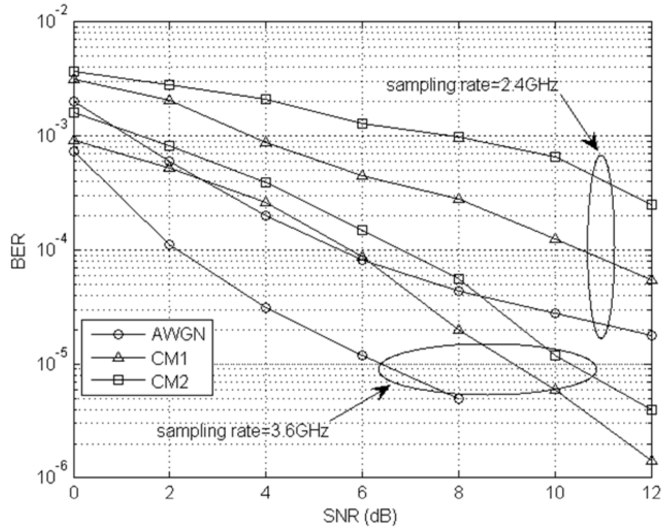

Fig. 2. Block diagram of the proposed JCES algorithm.

$|sum(n)|$ exceeds a predefined $threshold$ ($0 < threshold < 1$), the coarse synchronization is successful.

2) When i is less than $N_{p1} + N$, sign bit of φ_i is always +1 (N_w is an even number). After capturing the frame, use two variables to judge the value of confidence, Λ and degree of confidence, Ψ. In the initial state, set Λ equal to 1 and Ψ equal to $[0, 0, \ldots, 0, 0]$, whose length is λ ($\lambda + N_w \leq N_{p1}$), and λ is a positive integer. In the acquisition state, if sign bit of φ_i is equal to Λ , refresh Ψ as $[1, \Psi(1 : \lambda - 1)]$; and in other cases, set Ψ equal to $[0, \Psi(1 : \lambda - 1)]$. If the sum of each element of Ψ is bigger than ν ($\nu < \lambda$), the acquisition progress is successful. And $sum_i(n)$ is the initial estimation of $q(n)$, which is a sampled version of the response of $h(t)$ to $p(t)$.

3) Because the timing error between the transmitter and receiver (that is $\kappa \neq 0$), adjust the relative position of channel estimation and sampling data. In this letter, we propose an algorithm based on minimum sum of the fixed interval. It is defined that and

$$chest_{ini}(n) = sum_i(n) - sum_i(n - C) \qquad n = 0, 1, \cdots, 2C - 1 \tag{20}$$

The searching process can be express as

$$\mathrm{M}(k) = \sum_{i=k}^{k+N_s-1} abs(chest_{ini}(k)) \quad k = 0, 1, \cdots, C \tag{21}$$

$$K = \arg\{\min_{k \in [0,C] \& k \in Z} (M(k))\} + N_s - 1 \tag{22}$$

where N_s is the searching length ($N_s < C$), Z denotes the integer domain. The adjusted channel estimation is

$$\hat{q}(n) = \begin{cases} chest_{ini}(K + 1 + n), & K < \frac{T_p}{T_s} \\ chest_{ini}(K - C + 1 + n), & K \geq \frac{T_p}{T_s} \end{cases} \tag{23}$$

where $\hat{q}(n)$ is the final estimation of $q(n)$, and $n = 0, 1, \ldots, C - 1$. The received data is sampled and adjusted correspondingly. Then correlation detection is performed to detect the data. The preamble is "+1" and "-1" alternatively, so in some case, there exists a sign change between the estimation result and the true channel, which will be found and corrected by the following payload synchronization sequence.

IV. Simulation Results

Fig. 2 shows the simulation results of the impulse UWB system on the AWGN, CM1, and CM2 channel models [9], respectively. The monocycle is in the 4.2-4.8GHz, and sampling rate is 2.4GHz and 3.6GHz respectively with 1 bit quantization. In the simulated system, $T_d = 10$ ns, and $Y = 8$; $N_{p1} = 500$, $N_p2 = 16$, and $N_w = 300$; $threshold = 0.6$, $\lambda = 200$, and $\nu = 198$; $N_s = T_d/T_s$. The payload consists of 10000 bits. Fig. 2 shows the average bit error ratio (BER) performance of 100 frames. The proposed JCES algorithm in this letter works well in the AWGN, CM1 and CM2 channels. After channel estimation and synchronization, correlation detection is used and the correlation length is Tp/Ts. As seen from the simulation results, because the quantization precision is 1 bit, the higher sampling rate, the better performance. This JCES algorithm is suitable for high-precision quantization.

V. Conclusion

In this letter, we propose a joint channel estimation and synchronization algorithm for IR-UWB system. The proposed algorithm is designed for high-speed sampling and 1-bit quantization. Acquisition and coarse channel estimation is first achieved. Then a minimum sum algorithm is proposed to adjust the channel estimation result and achieve sample level synchronization. Correlation detection based on the channel estimation and synchronization results are recommended for data recovery. Simulation results show that the proposed algorithm works well in AWGN, CM1, and CM2 channels.

References

[1] I. Oppermann, *UWB Theory and Application*. John Wiley & Sons, Ltd., 2004.

[2] ECMA International, Standard ECMA-368-High Rate Ultra Wideband PHY and MAC Standard, Rue du Rhone 114 CH-1204 Geneva, Dec 2005.

[3] M. Win and R. Scholtz, "On the energy capture of ultrawide bandwidth signals in dense multipath environment," *IEEE Commun. Lett.*, vol. 2, pp. 245-247, Sep. 1998.

[4] J. D. Choi and W. E. Stark, "Performance of ultra-wideband communications with suboptimal receivers in multipath channels," *IEEE J. Sel. Areas Commun.*, vol. 20, no. 9, pp. 1754-1766, Dec. 2002.

[5] C. Carbonelli and U. Mengali, "Synchronization algorithms for UWB singals," *IEEE Trans. Commun.*, vol. 54, pp. 329-337, Feb. 2006.

[6] L. Yang and G. B. Giannakis, "Timing ultra-wideband signals with dirty templates," *IEEE Trans. Commun.*, vol. 53, no. 11, pp. 1952-1963, Nov. 2005.

[7] J. Wang and L. B. Milstein, "CDMA overlay situations for microcellular mobile communications," *IEEE Trans. Commun.*, vol. 43, no. 2/3/4, pp. 603-614, Feb./Mar./Apr. 1995.

[8] J. Wang and J. Chen, "Performance of wideband CDMA systems with complex spreading and imperfect channel estimation," *IEEE J. Sel. Areas Commun.*, vol. 19, pp. 152-163, Jan. 2001.

[9] J. Foerster, Channel modeling sub-committee report final[J], IEEE P802.15 Working Group Document, no. IEEE P802. 15-02/368r5, Nov. 2002.