Channel Estimation and Signal Detection for UWB

Li, Y.

TR2003-74   November 2003

Abstract

In this paper, we investigate channel estimation and signal detection for UWB communications. We first investigate channel estimation for UWB systems and then develop a minimum mean-square-error (MMSE) Rake receiver with joint timing and MMSE equalization. The key property of the estimator is that it uses sampling at UWB symbol rate (200Msamples/s), while estimating all relevant channel parameters for the full 7.5 GHz channel bandwidth. Computer simulations verify the usefulness of our approach for channel estimation and signal detection.

Publication History:

1. First printing, TR-2003-74, November 2003

Channel Estimation and Signal Detection for UWB

Ye (Geoffrey) Li, *Senior Member, IEEE*
Georgia Institute of Technology

Andreas F. Molisch, *Senior Member, IEEE* and Jinyun Zhang *Senior Member, IEEE*
Mitsubishi Electric Research Labs

Abstract: *In this paper, we investigate channel estimation and signal detection for UWB communications. We first investigate channel estimation for UWB systems and then develop a* minimum mean-square-error *(MMSE) Rake receiver with joint timing and MMSE equalization. The key property of the estimator is that it uses sampling at UWB symbol rate (200Msamples/s), while estimating all relevant channel parameters for the full 7.5 GHz channel bandwidth. Computer simulations verify the usefulness of our approach for channel estimation and signal detection.*

I. Introduction

Ultra-wideband (UWB) communications systems spread the data over a very large transmission bandwidth (at least 500MHz according to FCC regulations), using a low power spectral density. One of the possible applications of UWB is the transmission of data at a high rate within a short range – something of special interest for future home networks. The IEEE is currently in the process of standardizing UWB high data rate communications in its standards group 802.15.3a.

The most popular approach for realizing UWB communications is time hopping impulse radio [1]. It allows a very simple transmitter structure that consists of only a baseband pulse generator, completely obviating the need for passband components like mixers, local oscillators, etc. However, the implementation of the receiver can be considerably more complex in a multipath environment, requiring a Rake receiver. A digital implementation of the Rake requires very high sampling and processing speed, both during the channel estimation and the actual data reception.

We have therefore recently suggested a modified Rake receiver structure that uses a mixture of analog and digital devices, allowing sampling and processing of data at the (unspread) *symbol* rate instead of the chiprate [5]. However, like any Rake structure, it needs the *complete* channel state information (estimate of the channel over the bandwidth of the spread bandwidth).

In this paper, we introduce a receiver and training sequence structure that can obtain this full information with symbol-rate sampling, i.e., with the same low-complexity that our new data reception uses.

The remainder of the paper is organized the following way: Sec. II describes the system structure, including the Rake receiver and equalizer. Section III describes the principles of our new parameter estimation technique. Simulation results in Sec. IV show the validity of our approach, and detail the performance that can be achieved with it. A summary wraps up the paper.

II. System model

II.A. Transmit signal

To satisfy the spectrum masking requirement of the FCC, the shaping pulse, or also known as monocycle waveform in [1], is chosen to be the 5th derivative of the Gaussian function and it can be expressed as,

$$p(t) = K_2\left(-15\frac{t}{\sigma} + 10\frac{t^3}{\sigma^3} - \frac{t^5}{\sigma^5}\right)e^{-\frac{t^2}{2\sigma^2}},$$

where σ controls the width of the pulse and it is chosen according to the spectral mask requirement of the FCC, which is,

$$\sigma = 5.28\times 10^{-11}.$$

Then a spread waveform can be obtained from the shaping pulse by

$$w(t) = \sum_{k=0}^{7} s_k p\left(t - kT_c\right),$$

where T_c =0.625 nsec and the spreading sequence, { s_k }={-1, +1, +1, -1, +1, +1, -1, -1}. Therefore, the symbol duration will be $T_s = 8T_c = 5$ nsec. Let

$\{b_k\}$ be a sequence to be transmitted. Then the modulated signal can be expressed as

$$s(t) = \sum_{k=-\infty}^{\infty} b_k w(t - kT_s).$$

Other signals shapes are possible; in particular, a combination of weighted pulses *p(t)* can be used to improve the spectral properties [4]; the principle of our approach is independent of the exact pulseshape.

II.B. Received Signal

The proposed UWB receiver structure is shown as in Figure 1, which mixes analog and digital processing. The receiver frond end and the filter matching the spread waveform *w(t)* are implemented using analog devices and the rest is digital processing.

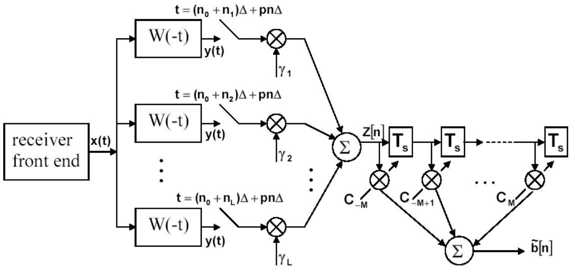

Figure 1: Receiver Structure

Let the impulse response of a UWB channel be

$$h(t) = \sum_k \alpha_k \delta(t - \tau_k),$$

where τ_k and α_k are the delay and (real) gain of the k-th path of the UWB channel, respectively. Then the channel output can be expressed as

$$\begin{aligned} x(t) &= h(t) * s(t) + n(t) \\ &= \sum_{n=-\infty}^{\infty} b_n \sum_k \alpha_k w(t - \tau_k - nT_s) + n(t) \qquad (1) \\ &= \sum_{n=-\infty}^{\infty} b_n \hat{h}(t - nT_s) + n(t), \end{aligned}$$

where

$$\hat{h}(t) = \sum_k \alpha_k w(t - \tau_k).$$

As shown in Figure 1, the output of the matched filter can be expressed as

$$\begin{aligned} y(t) &= x(t) * w(-t) \\ &= \sum_{k=-\infty}^{\infty} b_k \tilde{h}(t - kT_s) + \tilde{n}(t), \end{aligned} \qquad (2)$$

where

$$\begin{aligned} \tilde{h}(t) &= \int \hat{h}(t - \tau) w(-\tau) d\tau \\ &= \sum_k \alpha_k r(t - \tau_k), \end{aligned} \qquad (3)$$

$$r(t) = \int w(t + \tau) w(\tau) d\tau,$$

and

$$\tilde{n}(t) = n(t) * w(-t). \qquad (4)$$

II.C. Rake Receiver

Let the samples *y[n]=y(Δn)* of the matched filter output be

$$\begin{aligned} y[n] &= \sum_{k=-\infty}^{\infty} b_k \tilde{h}(n\Delta - kT_s) + \tilde{n}(n\Delta) \\ &= \sum_{k=-\infty}^{\infty} b_k \tilde{h}(n\Delta - kp\Delta) + \tilde{n}(n\Delta), \end{aligned} \qquad (5)$$

where Δ=0.15625 ns (the inverse of the 7.5GHz bandwidth) is the minimum time difference among Rake fingers and $p = T_S / \Delta = 32$.

As in Figure 1, the Rake receiver with L (=10) fingers is used to collect signal energy and mitigate intersymbol and other interference. Let $\tilde{h}(n_l\Delta)$'s, for l=1, …, L be the L taps with the largest absolute values, $\left|\tilde{h}(n_l\Delta)\right|$'s. The output of the Rake receiver can be expressed as

$$z[n, n_o] = \sum_{l=1}^{L} \gamma_l \, y[pn + n_l + n_o]. \qquad (6)$$

where γ_l is the weight for the *l*-th finger and n_o is a time offset. It is obvious that the signal quality of the RAKE receiver output depends on the weight and initial time offset.

Maximal ratio (MR) combining is a traditional approach to determine the weights of the Rake combiner. For the MR Rake combiner, $\gamma_l = \tilde{h}(n_l\Delta)$, and

$$z[n, n_o] = \sum_{l=1}^{10} \tilde{h}(n_l\Delta) y[pn + n_l + n_o].$$

Minimum mean-square-error (MMSE) Rake combining can improve the performance of the Rake receiver in the presence of interference. For the MMSE Rake combiner, the weights are chosen to minimize

$$E\left|z[n, n_o] - b_n\right|^2.$$

The performance of the Rake receiver can be further improved if adaptive timing is used with the MMSE Rake combiner. That is, the goal is to find *optimum time* offset n_o and γ_l to minimize

$$E\left|z[n,n_o]-b_n\right|^2 .$$

II.D. Channel Equalizer

After the Rake receiver, a linear equalizer is used to mitigate residual interference. Let the coefficients of the equalizer be $\{c_{-K},...,c_{-1},c_0,$ $c_1,...,c_K\}$ (K=2). Then the equalizer output is

$$\tilde{b}[n]=\sum_{k=-2}^{2}c_k z[n-k,n_o].$$

To optimize performance, the equalizer coefficients are chosen to minimize the MSE of its output, that is

$$MSE=E\left|\tilde{b}[n]-b_n\right|^2 .$$

III. Parameter Estimation

In the previous section, we have introduced a signal detection approach for the UWB receiver. In this section, we will focus on channel, Rake, and equalizer parameter estimation.

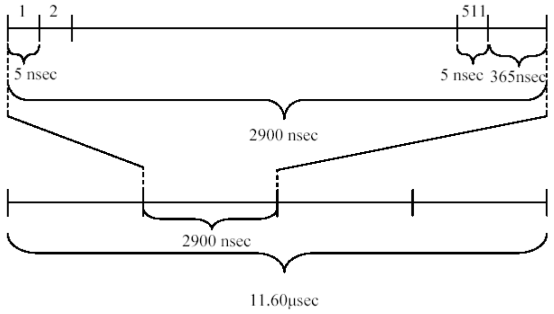

Figure 2. Structure of the training sequence

A training sequence is used for the determination of the parameters. The structure of the training sequence is shown in Figure 2. From the figure, 11.6 μs off training are used to estimate channel coefficients, weights for Rake combining, and equalizer coefficients. The matched filters shown in Fig. 1 are used for the channel estimation; from a complexity point of view, it is highly desirable not to have additional hardware for the channel estimation.

III.A. Channel Estimation

The matched filter in the Rake receiver in UWB systems is implemented using analog circuits since it needs to operate at a high speed. The output of the matched filter is sampled at symbol rate ($1/T_s=1/(p\Delta)$). Therefore, during each symbol period, we can only observe *L* outputs, each for one of *L* fingers. On the other hand, we need to estimate channel coefficients every Δ sec; thus we need to obtain p (=32) uniform samples during each symbol period.

In order to solve this seeming paradox, we use an approach that shows some similarity to the "swept time delay cross correlator" channel sounder proposed by D. Cox in [2]. We repeatedly send the same training sequence with guard interval 4 times to obtain denser sampling of the matched filter output. Each training sequence consists of 511 symbols (PN sequence) and 365 nsec guard interval to prevent interference caused by delay spread of UWB channels between adjacent training sequences. Consequently, the length of the whole training period for parameter estimation is 4(511*5+365)=11600 ns or 11.6 μsec.

To obtain a higher rate and uniform samples, $y_t(n\Delta)$, the timing of the l-th finger corresponding to the m-th training sequence is adjusted as follows:

$$t_{l,m}=4(l-1)\Delta+(m-1)\Delta,$$

for $l=1,\cdots,10,$ and $m=1,\cdots 4.$

Let the training sequence be b_k^t's for k=0, 1, …, 510. Then the training signal can be expressed as

$$s_t(t)=\sum_{k=0}^{510}b_k^t w(t-kT_s),$$

and the channel output is

$$x_t(t)=h(t)*s_t(t)+n(t),$$

where $h(t)$ is the channel's impulse response and $n(t)$ is the *additive white Gaussian noise* (AEGN).

The Δ-spaced output of the matched filter will be

$$\begin{aligned}y_t(n\Delta)&=\int x_t(n\Delta+\tau)w(\tau)d\tau\\&=\sum_{k=0}^{510}b_k^t\tilde{h}(n\Delta-kp\Delta)+\tilde{n}(n\Delta).\end{aligned}$$

Channel parameters can be directly estimated by

$$\tilde{h}(n\Delta)=\frac{1}{511}\sum_{k=0}^{510}b_k^t y_t(n\Delta+kp\Delta).$$

III.B. Rake Weight Estimation

Once channel parameters are estimated, we can find the 10 taps with the largest absolute value. Let $n_1,\cdots,n_{10}$ be the index of the 10 taps. Then the weights for the MMSE Rake combiner and optimum timing can be found by minimizing

$$\begin{aligned} &MSE(\vec{\gamma}, n_o) \\ &= \frac{1}{511}\sum_{n=0}^{510}\left| z_t\,[n, n_o] - b_n^t \right|^2 \\ &= \frac{1}{511}\sum_{n=0}^{510}\left| \sum_{l=1}^{10} \gamma_l y_t\,[pn + n_l + n_o] - b_n^t \right|^2 . \end{aligned}$$

Direct calculation yields that

$$\vec{\gamma} = \begin{pmatrix} \gamma_1 \\ \vdots \\ \gamma_{10} \end{pmatrix} = \left(\mathbf{Y}_t \mathbf{Y}_t^H\right)^{-1}\left(\mathbf{Y}_t \mathbf{b}_t^H\right),$$

where

$$\mathbf{Y}_t = \begin{pmatrix} y_t\,[n_1 + n_o] & \cdots & y_t\,[510p + n_1 + n_o] \\ y_t\,[n_2 + n_o] & \cdots & y_t\,[510p + n_2 + n_o] \\ \vdots & \cdots & \vdots \\ y_t\,[n_{10} + n_o] & \cdots & y_t\,[510p + n_{10} + n_o] \end{pmatrix},$$

and

$$\mathbf{b}_t = \begin{pmatrix} b_0^t & b_1^t & \cdots & b_{510}^t \end{pmatrix}.$$

III.C. Equalizer Coefficient Estimation

From the estimated weights for the Rake receiver, its output can be calculated by

$$z_t\,[n, n_o] = \sum_{l=1}^{10} \gamma_l y_t\,[pn + n_l + n_o].$$

The equalizer coefficients can be estimated by minimizing

$$\frac{1}{511}\sum_{n=0}^{511}\left| \sum_{k=-2}^{2} c_k z_t\,[n-k, n_o] - b_k^t \right|^2 .$$

Consequently,

$$\begin{pmatrix} c_{-2} \\ \vdots \\ c_2 \end{pmatrix} = \left(\frac{1}{511}\sum_{k=0}^{510} \mathbf{z}_k^t \mathbf{z}_k^{t\,T} \right)^{-1} \left(\frac{1}{511}\sum_{k=0}^{510} \mathbf{z}_k^t b_k^t \right),$$

where

$$\mathbf{z}_k^t = \begin{pmatrix} z_t\,[k+2, n_o] \\ \vdots \\ z_t\,[k-2, n_o] \end{pmatrix}. \qquad (12)$$

IV. Performance Evaluation

In this section, we evaluate performance of a UWB system with our channel estimation scheme through computer simulation. In our simulation, 4 types of standard IEEE 802.15.3a channel models [3], CM1, CM2, CM3, and CM4, are used. For each type of channel model, 100 trials are generated to evaluate by average *bit-error-rate* (BER) and *normalized MSE* (NMSE).

IV.A. System Simulation

Due to extremely broad bandwidth of UWB systems, it is very complicated if an oversampled system is used to simulate the corresponding continuous system as we do for traditional communication systems. Therefore, we start with Δ- space sampled system (Eq. (5)) to study the performance of the overall UWB system, that is,

$$y[n] = \sum_{k=-\infty}^{\infty} b_k \tilde{h}(n\Delta - kp\Delta) + \tilde{n}(n\Delta). \qquad (13)$$

The $\tilde{h}(n\Delta)$ and $\tilde{n}(n\Delta)$ in the above equation are generated by

$$\tilde{h}(n\Delta) = \sum_k \alpha_k r(n\Delta - \bar{k}\delta),\ \bar{k} = \left\lfloor \frac{\tau_k}{\delta} + 0.5 \right\rfloor,$$

and

$$\tilde{n}(n\Delta) = \sum_k n[n] w(n\Delta - k\Delta),$$

respectively, where $\lfloor x \rfloor$ denotes the largest integer less than x. In our simulation, $\delta = 3.125 \times 10^{-12}$ sec $= 3.125\ p\text{sec}$ ($\Delta = 50\delta$), $n(k\Delta)$'s for different k's are independent Gaussian with zero-mean and a variance determined by E_b / N_o.

In our study, we are using E_b / N_o to indicate the relative levels of the desired signal and noise. However, SNR, the ratio of the desired signal power and the noise power in the matched filter output, y[n], is sometimes used by some researchers. For the system used here,

SNR (dB) = E_b / N_o (dB) -14 .0 (dB).

IV.B. Performance of Channel Estimation

Figure 3 shows performance of channel estimation. From Fig. 3(a), channel estimation improves with signal-to-noise ratio when E_b / N_0 is less than 25 dB. However, when it is over 35 dB, there is an error floor. Fig. 3(b) shows the NMSE of the 10 largest channel taps, which is much better than the NMSE of overall channel estimation.

IV.C. Performance Improvement of Different Techniques

Figure 4 shows performance improvement of different techniques developed in this paper. The combination of a 10-finger ML Rake receiver with a

5-tap equalizer results in error floors for CM-3 and CM-4 at raw BERs of 10^{-3} and 5×10^{-3}, respectively. However, when a 10-finger MMSE Rake receiver is used, the error floors are reduced to below 10^{-4} and 3×10^{-4}, respectively. Therefore, the MMSE Rake receiver can significantly improve performance of UWB systems.

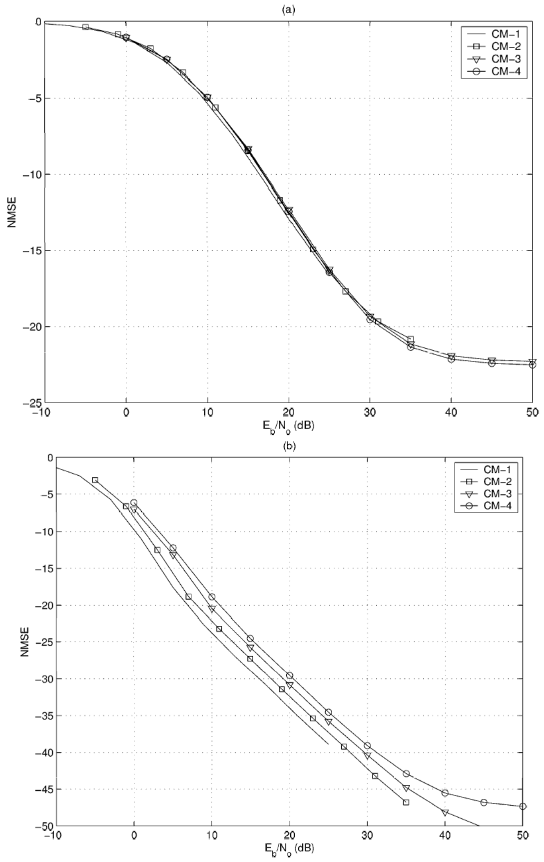

Figure 3. NMSE of (a) overall channel estimation and (b) 10 largest channel taps

Figure 4 also demonstrates performance improvement of adaptive timing. By using adaptive timing, the error floor is reduced from 1.5×10^{-3} to 3×10^{-4} for CM-4.

VI. Conclusions

In this paper, we investigated channel estimation and signal detection for UWB systems. We designed training head to estimate channel parameters. We used combination of a Rake receiver and a simple equalizer to deal with delay spread of UWB channel and detection signal. The proposed approaches are with low complexity can be directly used in the UWB communication systems.

Acknowledgment: The authors would like to thank Dr. Philip Orlik for useful discussions.

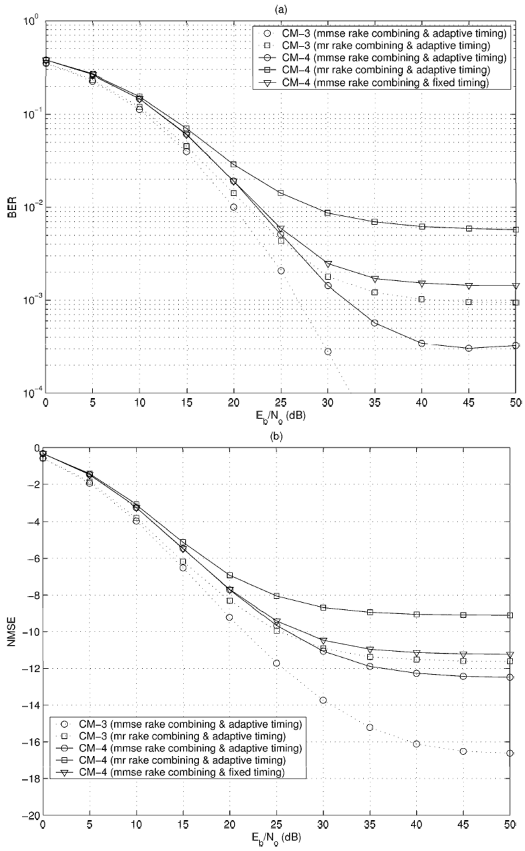

Figure 4. Performance comparison of different signal detection techniques

References

[1] M. Z. Win and R. A. Scholtz, "Ultra-wide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communications," *IEEE Trans. on Comm.*, vol. 48, pp. 679-691, April 2000.

[2] D. C. Cox, "Delay Doppler characteristics of multipath propagation at 910 MHz in suburban mobile radio environment," *IEEE Trans. on Antennas and Prop.*, vol 20, pp. 625-635, Sept. 1972.

[3] J. Foerster (editor), "Channel Modeling Sub-committee Report Final," IEEE802.15-02/490 (see http://ieee802.org/15/)

[4] Y. Wu, A. F. Molisch, S. Y. Kung, and J. Zhang, "Impulse Radio Pulse Shaping for Ultra-Wide Bandwidth UWB Systems", submitted to PIRMC 2003.

[5] A. F. Molisch et al., "A flexible low-complexity system for high data rate UWB communications, submitted to WPMC 2003.