Receiver Techniques for Ultra-wide-band Multiuser Systems over Fading Multipath Channels

Xiaobo Zhou and Xiaodong Wang

Abstract: **We treat the problem of channel estimation and interference cancellation in multiuser ultra-wide-band (UWB) communication systems over multipath fading channels. The UWB system under consideration employs a random time-hopping impulse radio format. We develop a channel estimation method based on linear weighted algorithm. An iterative channel estimation and interference cancellation scheme is proposed to successively improve the receiver performance. We also consider systems employing multiple transmit and/or receive antennas. For systems with multiple receive antennas, we develop a diversity receiver for the well-separated antennas. For systems with multiple transmit antennas, we propose to make use of Alamouti's space-time transmission scheme, and develop the corresponding channel estimation and interference cancellation receiver techniques. Simulation results are provided to demonstrate the performance of various UWB receiver techniques developed in this paper.**

Index Terms: **Ultra-wide-band communication system, multipath fading, pilot-aided channel estimation, channel re-estimation, interference cancellation, space-time coding, diversity.**

I. INTRODUCTION

Impulse radio (IR) is an emerging ultra-wide-band wireless communication technology [1], [2], [3], [4], [5], [6], [7], [8]. It transmits information using a train of pulses of very short duration, typically on the order of a nano-second, thereby spreading the transmission power from several KHz to a few GHz, resulting in very low power spectral density. With such significant bandwidth, a multiple-access impulse radio system can accommodate many users, even in multipath fading environments. In this paper, we treat the problems of channel estimation and interference cancellation for multiuser UWB systems employing single and multiple transmit and/or receive antennas.

Specifically, we assume each user transmits pilot symbols to assist channel estimation. The linear-weight-based channel estimator is considered. We then propose a receiver scheme that performs iterative channel estimation and interference cancellation. When the system employs multiple receive antennas, we develop the receiver technique, namely, the diversity receiver for well-separated antennas. Finally, when the system employs multiple transmit antennas, we propose to employ the space-time block coding transmission technique, and develop the corresponding receiver methods for channel estimation and interference cancellation.

The rest of this paper is organized as follows. In Section II, we describe the multiuser impulse radio system and the general receiver structure. In Section III, we develop one channel estimation method for UWB systems, as well as the diversity receiver for systems with multiple receive antennas. In Section IV, receiver techniques for UWB systems employing multiple transmit antennas and space-time coding are discussed. In Section V, we conclude the paper.

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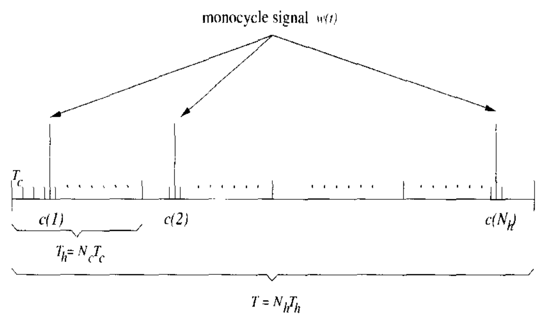

Fig. 1. A typical time-hopping impulse radio signal corresponding to one data symbol.

II. SYSTEM DESCRIPTIONS

A. Impulse Radio Signal Model

Consider a typical time-hopping [5] impulse radio binary communication system. The transmitted waveform corresponding to one data symbol is depicted in Figure.

The symbol consists of N_h time-hops over a total symbol duration T, hence the hop duration is $T_h = T/N_h$. Each hop is further split into N_c chips, and the chip interval is given by $T_c = (T_h - T_g)/N_c$, where T_g is a guard time introduced to account for processing delay at the receiver between two successive hops. For the j-th hop, a monocycle waveform $w(t)$ is transmitted at the $c(j)$-th chip position, shifted by δb where $b \in \{0, 1\}$ is the data bit. In summary, the transmitted signal corresponding to one data symbol is given by

$$s(t) = \sum_{j=0}^{N_h-1} w\Big(t - jT_h - c(j)T_c - \delta b\Big), \quad 0 \leq t < T. \quad (1)$$

The duration of a single monocycle is much less than one chip interval. For example, a typical Gaussian monocycle signal is given by [9]

$$w(t) = \left[1 - \left(\frac{t}{\sigma}\right)^2\right] \exp\left[-\frac{t^2}{2\sigma^2}\right], \quad (2)$$

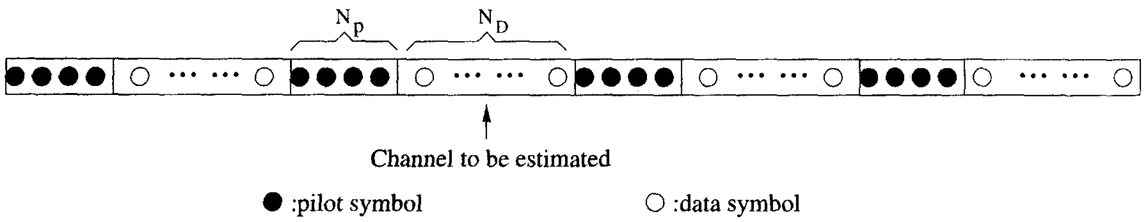

Fig. 2. Transmitted signal frame structure.

where σ is a pulse width parameter. The effective time duration of the Gaussian monocycle is set as $T_p \triangleq 7\sigma = 0.5$ns [9]. In this paper, we assume for simplicity that $T_g = 0$. In fact, the model encompasses the case $T_g \neq 0$ as well, by setting $T_g = N_g T_c$, with N_g being an integer and restricting the sequence $c(j)$ to take its value in $[0, N_c' - 1]$ where $N_c' = N_c - N_g$.

Assume that M symbols are transmitted, then the transmitted signal can be written as

$$x(t) = A \sum_{i=0}^{M-1} \sum_{j=0}^{N_h-1} w\Big(t - jT_h - c(i,j)T_c - \delta b(i) - iT\Big), \quad (3)$$

where A is signal amplitude and $c(i,j)$ denotes the j-th chip of the hopping sequence corresponding to symbol i ($b(i)$). In an AWGN channel, the received signal $r(t)$ is given by

$$r(t) = x(t - \tau) + n(t), \quad (4)$$

where τ is the propagation delay, and $n(t)$ is a circularly symmetric complex white Gaussian noise process with zero-mean and power spectral density σ^2. The optimal receiver in this case is the pulse correlative receiver (i.e., matched filter), given by

$$\psi(t) = w(t - \delta) - w(t). \quad (5)$$

In order to demodulate the i-th symbol, we compute the following sufficient statistic

$$r(i) = \frac{1}{T} \sum_{j=0}^{N_h-1} \int_{\tau+iT+jT_h}^{\tau+iT+(j+1)T_h} r(t) \, \psi\Big(t - jT_h - c(i,j)T_c - iT - \tau\Big) dt. \quad (6)$$

From (3) and (4), it is easy to see that

$$r(i) = [2b(i) - 1] \cdot A + n(i), \quad (7)$$

where $n(i) \sim \mathcal{N}_c(0, \sigma^2)$. A decision is made according to

$$\hat{b}(i) = \mathcal{S}\Big(\Re\{r(i)\}\Big) \triangleq \begin{cases} 1, & \text{if } \Re\{r(i)\} > 0 \\ 0, & \text{if } \Re\{r(i)\} \leq 0. \end{cases} \quad (8)$$

B. Multiuser Impulse Radio System in Multipath Fading Channels

Consider an impulse radio system with K users. The symbol sequence of each user is divided into a sequence of slots. Each slot contains N_P pilot symbols followed by N_D data symbols as shown in Fig. 2. Hence the size of each time slot is $N_S = N_P + N_D$. The transmitted signal by user k is given by

$$x_k(t) = A_k \sum_{i=0}^{M-1} \sum_{j=0}^{N_h-1} w\Big(t - jT_h - c_k(i,j)T_c - \delta b_k(i) - iT\Big), \quad k = 1, \cdots, K, \quad (9)$$

where A_k is the signal amplitude of the k-th user; $\{c_k(i,j)\}$ is the pseudo random hopping sequence for the k-th user's i-th symbol, and $b_k(i) \in \{0, 1\}$ is the i-th binary symbol of the k-th user. The signal of the k-th user is then transmitted through a multipath Rayleigh fading channel with a time-variant impulse response [1], [2], [3], [10], [11], given by

$$h_k(t) = \sum_{i=0}^{M-1} \sum_{l=1}^{L} g_{kl} \delta(t - iT - \tau_{kl}), \quad (10)$$

where L is the number of paths in each user's channel; g_{kl} and τ_{kl} are respectively the complex gain corresponding to symbol i and the delay of the l-th path of the k-th user's channel. The received signal at the receive antenna is the superposition of the K users' channel-distorted plus signals and the additive white Gaussian noise, given by

$$\begin{aligned} r(t) &= \sum_{k=1}^{K} x_k(t) * h_k(t) + n(t) \\ &= \sum_{k=1}^{K} A_k \sum_{i=0}^{M-1} \sum_{j=0}^{N_h-1} \sum_{l=1}^{L} g_{kl} w\Big(t - jT_h \\ &\qquad - c_k(i,j)T_c - \delta b_k(i) - iT - \tau_{kl}\Big) + n(t), \end{aligned} \quad (11)$$

where $*$ denotes convolution.

We adopt the statistical multipath fading channel model for UWB system introduced in [10] to simulate channel gain g_{kl}. Nakagami-m distribution is used to simulate the channel gain in [10]. It has the density function

$$f(x) = \frac{2m^m x^{2m-1}}{\Gamma(m)\Omega^m} \exp(-\frac{mx^2}{\Omega}), \quad (12)$$

where $\Omega = \mathbb{E}[x^2]$ and $\Gamma(x)$ is the Gamma function. In this study, m is set as 1 and the parameter Ω follows an exponential distribution whose details are described in [1], [10]. In this case, the distribution above is reduced to Raleigh distribution. Just as the authors pointed out in [5], a Rayleigh distribution, whose distribution $f(x) = \frac{x}{\alpha^2}\exp(-\frac{x^2}{2\alpha^2})$ with $\alpha = 0.46$, represents the best-fit to the recovered UWB data when considering the Raleigh, log-normal, Nakagami-m, or Rician distributions as possibilities.

The receiver structure is based on iterative interference cancellation and channel estimation. It is assumed that the delays $\{\tau_{kl}\}$ are known to the receiver. For delay estimation, we refer to [12]. The received signal $r(t)$ is first processed by a bank of pulse correlation filters matched to the monocycle waveforms of all users at different delays, to obtain the following statistics

$$r_{kl}(i) = \frac{1}{T}\sum_{j=0}^{N_h-1}\int_{\tau_{kl}+iT+jT_h}^{\tau_{kl}+iT+(j+1)T_h} r(t) \psi\Big(t - jT_h - c(i,j)T_c - iT - \tau_{kl}\Big)dt. \quad l = 1,\cdots,L;\ k = 1,\cdots,K;\ i = 0,\cdots,M-1, \quad (13)$$

where $\psi(t)$ is given by (5). Based on $\{r_{kl}(i)\}$ and the values of the pilots symbols, in Section III.1, we will describe two methods for estimating the multipath fading channel responses $\{g_{kl}\}$. Let $\hat{g}_{kl}$ be an estimate of g_{kl}. Using maximal ratio combining, an initial estimate of the data symbol $b_k(i)$ is given by

$$\hat{b}_k(i) = \mathcal{S}\left[\Re\left\{\sum_{l=1}^{L}\hat{g}_{kl}^* r_{kl}(i)\right\}\right], \quad k = 1,\cdots,K;\ i = 0,\cdots,M-1. \quad (14)$$

Next, a parallel interference cancellation [13] is performed. The detected data symbols are time-multiplexed with the pilot symbols according to the same structure in Fig. 2. The k-th user's signals are then reconstructed using the estimated channels, to obtain $\hat{y}_k(t) = \hat{x}_k(t) * \hat{h}_k(t),\ k = 1,\cdots,K$. Interference cancellation is then performed for each user,

$$\hat{r}_k(t) = r(t) - \sum_{j=1, j\neq k}^{K}\hat{y}_j(t), \quad k = 1,\cdots,K. \quad (15)$$

Next, matched-filtering is performed on the post-cancellation signals $\hat{r}_k(t)$ to obtain $\hat{r}_{kl}(i)$. Based on the new statistic $\{\hat{r}_{kl}(i)\}$ and the pilots symbols, we estimate the multipath fading channels of each user again to obtain the new estimates $\{\tilde{g}_{kl}\}$. Finally, a refined estimate of the data symbol $b_k(i)$ is given by $\tilde{b}_k(i)$ similar to (14), where $\hat{g}_{kl}$ is replaced by $\tilde{g}_{kl}$. The above interference cancellation and channel estimation procedure can be repeated several times to improve the receiver performance.

III. RECEIVERS FOR SINGLE TRANSMIT ANTENNA SYSTEMS

In this section, we consider systems with a single transmit antenna. In Section III.1, we provide one method for channel estimation; in Section III.2, we discuss receiver techniques when multiple receive antennas are employed; and in Section III.3, we provide simulation results.

A. Channel Estimation Methods

In this section, we consider a method for estimating the multipath fading channels based on linear weighted pilot channel values.

In the weighted multi-slot averaging channel estimation method [14], the channel is estimated simply by a fixed linear interpolator. Define $\beta_k(i) = 2b_k(i) - 1$. Assuming the fading remains constant over the pilot symbol duration in one slot, the N_P consecutive pilot symbols are averaged first to obtain

$$\hat{\eta}_{kl}(m) = \frac{1}{N_P}\sum_{n=1}^{N_P} r_{kl}(mN_S+n)\beta_k(mN_S+n), \quad l = 1,\cdots,L,\ k = 1,\cdots,K, \quad (16)$$

where $\hat{\eta}_{kl}(m)$ approximates the instantaneous channel gain of the k-th user's l-th path at the central pilot position in the m-th slot. The channel coefficients corresponding to the information symbols are then obtained by a linear weighted pilot channels over $2J$ slots, i.e., $\hat{g}_{kl} = \sum_{j=-J+1}^{J}\alpha_j\hat{\eta}_{kl}(m+j)$, where $\{\alpha_j\}$ are the real-valued filter coefficients. In this paper, we use $J = 2$ and the corresponding filter coefficients are $1/(2J+1)$. Note that if the the fading channel is time-varying, the filter coefficients can be set according to [14] and [15] .

B. Diversity Receiver for Well-Separated Receive Antennas

We next address iterative channel estimation and interference cancellation in systems with multiple receive antennas. Assume that the base station receiver has two receive antennas spaced several wave-lengths apart, so that the fading at the two antennas can be regarded as independent. The received signal at the two receive antennas is given by

$$\underline{r}(t) = \sum_{k=1}^{K}A_k\sum_{i=0}^{M-1}\sum_{j=0}^{N_h-1}\sum_{l=1}^{L}\underline{g}_{kl}w\Big(t - jT_h - c_k(i,j)T_c - \delta b_k(i) - iT - \tau_{kl}\Big) + \underline{n}(t), \quad (17)$$

where $\underline{r}(t) = [r_1(t),\ r_2(t)]^T$, $\underline{n}(t) = [n_1(t),\ n_2(t)]^T$, and $\underline{g}_{kl} = [g_{kl,1},\ g_{kl,2}]^T$ with $g_{kl,p}$ being the channel value between the transmitter and the p-th receiver antenna. The matched filter output, $\underline{r}_{kl}(i) = [r_{kl,1}(i),\ r_{kl,2}(i)]^T$ is given by

$$\underline{r}_{kl}(i) = \frac{1}{T}\sum_{j=0}^{N_h-1}\int_{\tau_{kl}+iT+jT_h}^{\tau_{kl}+iT+(j+1)T_h}\underline{r}(t) \psi\Big(t - jT_h - c(i,j)T_c - iT - \tau_{kl}\Big)dt \quad l = 1,\cdots,L;\ k = 1,\cdots,K;\ i = 0,\cdots,M-1. \quad (18)$$

The channel coefficients $\{g_{kl,1},\ g_{kl,2}\}$ are estimated from each antenna. The estimation methods are the same as that described in Section III.1. Denote $\hat{g}_{kl,p}$ as the estimate of $g_{kl,p}$ and $\underline{\hat{g}}_{kl} =$

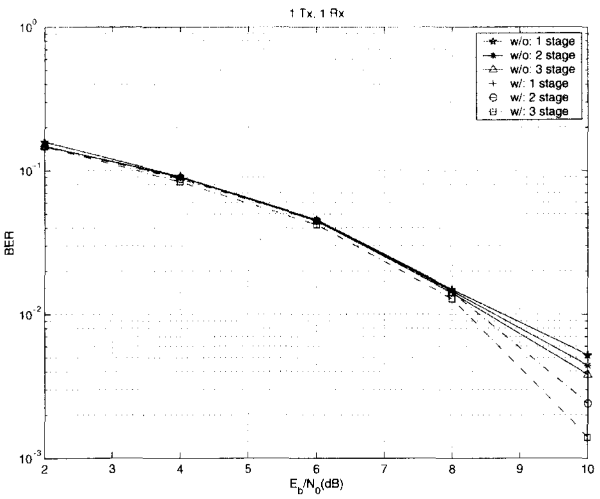

Fig. 3. Performance comparisons of the UWB multiuser systems employing iterative interference cancellation and with/without channel re-estimation.

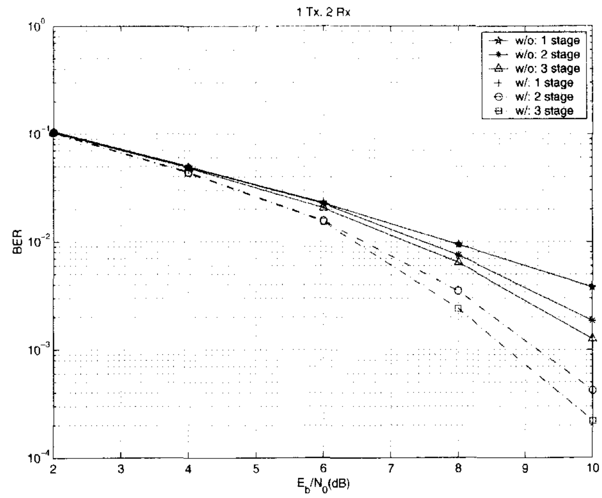

Fig. 4. Performance comparisons of UWB multiuser systems with two well-separated receive antennas, employing iterative interference cancellation with/without channel re-estimation.

$\left[\hat{g}_{kl,1},\ \hat{g}_{kl,2}\right]^T$. Then the initial estimate of the data symbol $b_k(i)$ is given by

$$\hat{b}_k(i) = \mathcal{S}\left[\Re\left\{\sum_{l=1}^{L}\hat{\underline{g}}_{kl}^H \underline{r}_{kl}(i)\right\}\right]. \tag{19}$$

Similarly to the technology in Section II, we can repeat the interference cancellation and channel estimation procedure several times to improve the receiver performance.

C. Simulation Results

The simulated multiuser system consists of 8 users, i.e., $K = 8$, and the time-hopping codes are periodic pseudo random with period $N_c = 15$. Each symbol consists of 15 hops, i.e., $N_h = 15$. All users have equal unit transmitted power, i.e., $A_1 = \cdots = A_K = 1$. The information symbols are time-multiplexed with pilot symbols in each slot. Each slot consists of 4 pilot symbols and 36 information symbols, i.e., $N_P = 4$, $N_D = 36$, $N_S = N_P + N_D = 40$. The symbol rate is 64K bits/sec. Each user's channel contains ten paths, i.e., $L = 10$. The relative path delays are $\tau_l = (l-1)\Delta t$ with $\Delta t = 4$ ns. The pulse width is $T_p = 0.5$ns.

Fig. 3 shows the performance of UWB multiuser receivers employing iterative interference cancellation with and without channel re-estimation. We can sen that the receivers with channel re-estimation can bring a larger performance gain than that without channel re-estimation. Moreover, a large performance gain of stage 2 and stage 3 in Fig. 3 is very significant for the receiver with channel re-estimation at higher SNR, but the performance gain of stage 3 is small for the receiver with channel re-estimation in Fig. 3. Meanwhile, the performance improvement is very small for the systems when SNR is lower. Note that normalization of the estimated channel coefficients from the previous stage is essential to achieving successive improvement of both channel estimation and symbol detection.

Fig. 4 shows the performance of UWB multiuser receivers with two well-separated receive antennas, employing iterative interference cancellation and with/without channel re-estimation. We can see that the receivers with channel re-estimation can bring a larger performance gain than that without channel re-estimation. Again, a large performance gain of stage 2 and stage 3 in Fig. 4 is very significant for the receiver with channel re-estimation, but the performance gain of stage 3 is small for the receiver with channel re-estimation in Fig. 4. Comparing with Fig. 3, we can see that the diversity receiver has brought significant performance improvement.

IV. RECEIVERS FOR MULTIPLE TRANSMIT ANTENNAS WITH SPACE TIME CODING

A. Receiver Structures

When two antennas are employed at the transmitter, we employ the simple Alamouti's space-time block coding transmission scheme [16]. Specifically, denote $s_k^{(i)}(t)$ as

$$s_k^{(i)}(t) = \sum_{j=0}^{N_h-1} w\Big(t - jT_h - c_k(i,j)T_c - \delta b_k(i)\Big),$$
$$0 \le t < T;\ \ i = 1,\cdots,M-1. \tag{20}$$

Then the following signals are transmitted across the k-th user's two transmit antennas.

$$x_k^{(1)}(t) = \sum_{i=0}^{M/2-1}\Big[s_k^{(2i)}(t-2iT) - s_k^{(2i+1)}(t-(2i+1)T)\Big], \tag{21}$$

$$x_k^{(2)}(t) = \sum_{i=0}^{M/2-1}\Big[s_k^{(2i+1)}(t-2iT) + s_k^{(2i)}(t-(2i+1)T)\Big]. \tag{22}$$

Assume one receive antenna is employed. Denote

$$g_k^{(p)}(t) = \sum_{i=0}^{M-1}\sum_{l=1}^{L} g_{kl}^{(p)}\delta\Big(t - iT - \tau_{kl}\Big),\ \ p = 1,2, \tag{23}$$

as the time-variant channel response between the p-th transmit antenna and the receive antenna. Assume that the fading between two adjacent transmitted symbols remains constant. The received signal is then given by

$$\begin{aligned} r(t) &= \sum_{k=1}^{K}\Big[x_k^{(1)}(t)\star g_k^{(1)}(t)+x_k^{(2)}(t)\star g_k^{(2)}(t)\Big]+n(t) \\ &= \sum_{k=1}^{K}\sum_{i=0}^{M/2-1}\sum_{l=1}^{L} g_{kl}^{(1)}\Big[s_k^{(2i)}(t-2iT-\tau_{kl}) - \\ &\qquad s_k^{(2i+1)}(t-(2i+1)T-\tau_{kl})\Big] + \\ &\sum_{k=1}^{K}\sum_{i=0}^{M/2-1}\sum_{l=1}^{L} g_{kl}^{(2)}\Big[s_k^{(2i+1)}(t-2iT-\tau_{kl}) + \\ &\qquad s_k^{(2i)}(t-(2i+1)T-\tau_{kl})\Big]+n(t). \end{aligned} \tag{24}$$

At the receiver, the pulse matched filter $\psi(t)$ in (5) is applied to the received signal $r(t)$ in (24) during each symbol interval, followed by space-time decoding. Specifically, denote

$$\begin{aligned} z_{kl}(2i) &\triangleq \frac{1}{T}\sum_{j=0}^{N_h-1}\int_{\tau_{kl}+2iT+jT_h}^{\tau_{kl}+2iT+(j+1)T_h} r(t) \\ &\quad \psi\Big(t-jT_h-c_k(2i,j)T_c-2iT-\tau_{kl}\Big)dt \\ &= g_{kl}^{(1)}\beta_k(2i)+g_{kl}^{(2)}\beta_k(2i+1)+u(2i), \end{aligned} \tag{25}$$

$$\begin{aligned} z_{kl}(2i+1) &\triangleq \Bigg[\frac{1}{T}\sum_{j=0}^{N_h-1}\int_{\tau_{kl}+(2i+1)T+jT_h}^{\tau_{kl}+(2i+1)T+(j+1)T_h} r(t) \\ &\quad \psi\Big(t-jT_h-c_k(2i+1,j)T_c-(2i+1)T-\tau_{kl}\Big)dt\Bigg]^* \\ &= -g_{kl}^{(2)^*}\beta_k(2i+1)+g_{kl}^{(1)^*}\beta_k(2i)+u(2i+1)^*, \end{aligned} \tag{26}$$

with $u(2i), u(2i+1) \sim \mathcal{N}_c(0,\sigma^2), \quad i=0,\cdots,M/2-1$.

Next, we discuss channel estimation method for this space-time coded systems. For simplicity, suppose the first transmitted N_P pilot symbols values are 1's. Then for $0 \le i < N_P/2-1$, we have

$$z_{kl}(2i) = g_{kl}^{(1)}+g_{kl}^{(2)}+u(2i), \tag{27}$$

$$z_{kl}(2i+1) = -g_{kl}^{(1)^*}+g_{kl}^{(2)^*}+u(2i+1)^*. \tag{28}$$

An initial estimation of the channel values corresponding to the pilot symbols are given by

$$\begin{aligned} \hat{g}_{kl}^{(1)} &= \frac{1}{2}\Re\Big[z_{kl}(2i)-z_{kl}(2i+1)\Big] \\ &\quad +\frac{i}{2}\Im\Big[z_{kl}(2i)+z_{kl}(2i+1)\Big], \end{aligned} \tag{29}$$

$$\begin{aligned} \hat{g}_{kl}^{(2)} &= \frac{1}{2}\Re\Big[z_{kl}(2i)+z_{kl}(2i+1)\Big] \\ &\quad +\frac{i}{2}\Im\Big[z_{kl}(2i)-z_{kl}(2i+1)\Big]. \end{aligned} \tag{30}$$

Based on the $N_P/2$ pilot channel values in the m-th slot at each transmit antenna, we obtain

$$\hat{\eta}_{kl}^{(p)}(m) = \frac{2}{N_P}\sum_{i=0}^{N_P/2-1}\hat{g}_{kl}^{(p)}\beta_k(mN_s+2i), \quad p=1,2. \tag{31}$$

The channel coefficients corresponding to the information symbols are then obtained by a linear weighted pilot channels over $2J$ slots, i.e.,

$$\hat{g}_{kl}^{(p)} = \sum_{j=-J+1}^{J}\alpha_j\hat{\eta}_{kl}^{(p)}(m+j), \tag{32}$$

where $\{\alpha_j\}$ are set as $1/(2J+1)$ in this study.

Based on the estimated channel values $\{\hat{g}_{kl}^{(p)},\ p=1,2\}$, we can make decisions on the data symbol as follows. Denote

$$\begin{aligned} \boldsymbol{z}_{kl}(2i) &\triangleq \begin{bmatrix} z_{kl}(2i) \\ z_{kl}(2i+1) \end{bmatrix}, \\ \hat{\boldsymbol{g}}_{kl}(2i) &\triangleq \begin{bmatrix} \hat{g}_{kl}^{(1)} \\ \hat{g}_{kl}^{(2)*} \end{bmatrix}, \\ \bar{\boldsymbol{g}}_{kl} &\triangleq \begin{bmatrix} \hat{g}_{kl}^{(2)} \\ -\hat{g}_{kl}^{(1)*} \end{bmatrix}. \end{aligned} \tag{33}$$

The initial decision rule for $b_k(2i)$ and $b_k(2i+1)$ is then given by

$$\begin{bmatrix} \hat{b}_k(2i) \\ \hat{b}_k(2i+1) \end{bmatrix} = \mathcal{S}\left(\Re\left\{\begin{array}{c} \sum_{l=1}^{L}\hat{\boldsymbol{g}}_{kl}^H\boldsymbol{z}_{kl}(2i) \\ \sum_{l=1}^{L}\bar{\boldsymbol{g}}_{kl}^H\boldsymbol{z}_{kl}(2i) \end{array}\right\}\right). \tag{34}$$

Next, a parallel interference cancellation is performed. The detected data symbols are time-multiplexed with the pilot symbols according to same structure in Fig. 2. The k-th user's signals are then reconstructed using the estimated channels to obtain

$$\begin{aligned} \hat{y}_k(t) &= \sum_{i=0}^{M/2-1}\sum_{l=1}^{L}\hat{g}_{kl}^{(1)}\Big[\hat{s}_k^{(2i)}(t-2iT-\tau_{kl}) \\ &\qquad -\hat{s}_k^{(2i+1)}(t-(2i+1)T-\tau_{kl})\Big] \\ &+\sum_{i=0}^{M/2-1}\sum_{l=1}^{L}\hat{g}_{kl}^{(2)}\Big[\hat{s}_k^{(2i+1)}(t-2iT-\tau_{kl}) \\ &\qquad +\hat{s}_k^{(2i)}(t-(2i+1)T-\tau_{kl})\Big], \\ &\qquad k=1,\cdots,K, \end{aligned} \tag{35}$$

where

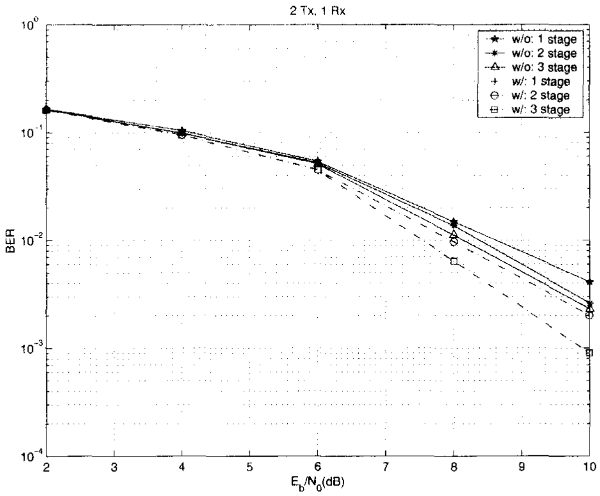

Fig. 5. Performance of UWB multiuser systems with space-time coding, employing iterative interference cancellation and with/ without channel re-estimation.

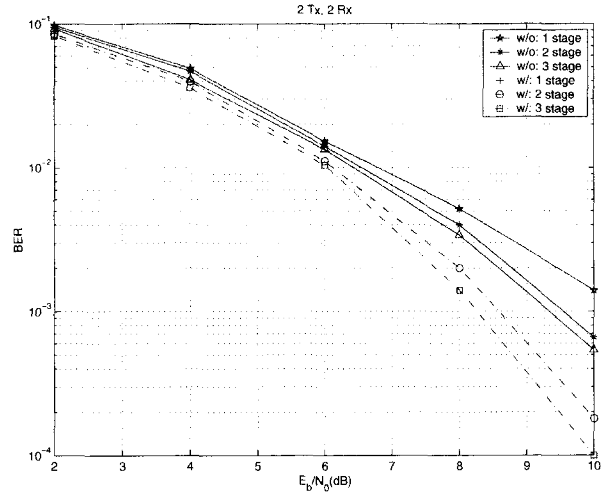

Fig. 6. Performance comparisons of UWB multiuser systems with space-time coding and two well-separated receive antennas, employing iterative interference cancellation and with and without channel re-estimation.

$$\hat{s}_k^{(i)}(t) = \sum_{j=0}^{N_h-1} w\Big(t - jT_h - c_k(i,j)T_c - \delta\hat{b}_k(i)\Big),$$
$$0 \le t < T; \; i = 0, \cdots, M-1. \quad (36)$$

An interference cancellation is then performed for each user,

$$\hat{r}_k(t) = r(t) - \sum_{j=1, j\neq k}^{K} \hat{y}_j(t), \quad k = 1, \cdots, K. \quad (37)$$

Next, matched-filtering is performed on the post-cancellation signals $\{\hat{r}_k(t)\}$

$$\hat{r}_{kl}(i) = \frac{1}{T}\sum_{j=0}^{N_h-1}\int_{\tau_{kl}+iT+jT_h}^{\tau_{kl}+iT+(j+1)T_h} \hat{r}(t)$$
$$\psi\Big(t - jT_h - c(i,j)T_c - iT - \tau_{kl}\Big)\,dt$$
$$l = 1, \cdots, L; \; k = 1, \cdots, K; \; i = 0, \cdots, M-1. \quad (38)$$

Now, based on the new statistic $\{\hat{r}_{kl}(i)\}$ and the pilot symbols, we estimate the multipath fading channels of each user again to obtain the new estimates $\{\tilde{g}_{kl}^{(p)}, p = 1, 2\}$, which in turn can be used to make a refined decision on the symbols similar to (34). The above interference cancellation and channel estimation procedure can be repeated several times to improve the receiver performance.

Finally, we note that if two receive antennas are employed at the receiver, we can similarly develop the diversity receiver as discussed in Section III.2.

B. Simulation Results

Fig. 5 shows the performance of UWB multiuser receivers with space-time coding and iterative interference cancellation with/without channel re-estimation. We can see that the receiver with channel re-estimation significantly outperforms the receiver without channel re-estimation. Comparing with Fig. 6, we can see that the performance of the receivers with space-time coding is worse than those without space-time coding when the SNR is lower, while the performance of the receivers with space-time coding is better than those without space-time coding when the SNR is higher.

Table 1. The SNR values required for 1% BER point for systems with and without STC.

	1 Rx, w/o CRE	1 Rx, with CRE	2 Rx, w/o CRE	2 Rx with CRE
w/o STC	8.5dB	8.2dB	7.2dB	6.5dB
with STC	7.5dB	8.1dB	5.2dB	4.9dB

Fig. 6 shows the performance of UWB multiuser receivers with space-time coding and two well-separated receive antennas, employing iterative interference cancellation and with/without channel re-estimation. We can see that the diversity receiver outperforms the receivers without diversity. And also, systems with space-time coding outperform systems without space-time coding in Fig. 3 and Fig. 4.

Finally, we also compare the performance of UWB systems with/without space-time coding. Table 1 lists the SNR values required for 1% BER point for systems with and without space-time coding (STC) where CRE means channel re-estimation. We can see that the systems with space-time coding slightly outperform systems without space-time coding for one receive antenna. The reason is that the channel estimation in the systems with space-time coding is more difficult than the channel estimation in the systems without space-time coding.

V. CONCLUSIONS

We have developed several receiver techniques for multiuser impulse radio communication systems over fading multipath channels. The contributions are summarized as follows. (1)

We have developed a pilot-symbol-aided channel estimation method. (2) We have developed an iterative channel estimation and interference cancellation scheme that successively improves the receiver performance. (3) For systems employing multiple receive antennas, we have developed a diversity receiver for the case of well-separated antennas. (4) For systems with multiple transmit antennas, we have proposed to employ the space-time block coding transmission scheme, and have developed the corresponding receiver techniques for channel estimation and interference cancellation.

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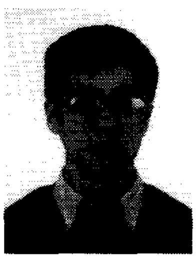

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