Zero-Forcing Based Prefiltering for Multiuser UWB System over Multiple-Input Single-Output Channels

Wei-Chiang Wu [1], #Hsin-Yuan Huang [2]
[1] Associate Professor, Department of Electrical Engineering, Da Yeh University, 112, Shan-Jiau Rd., Da-Tsuen, Changhua, Taiwan 515, R.O.C., E-mail: wcwm53@mail.dyu.edu.tw
[2] Department of Electrical Engineering, Da Yeh University, 112, Shan-Jiau Rd., Da-Tsuen, Changhua, Taiwan 515, R.O.C., E-mail: enthendin@yahoo.com.tw

1. Introduction

Recently, a lot of attention was paid to UWB IR systems since it is a promising technique for low-complexity low-power short range indoor wireless communications [1-3]. When such transmissions are applied in multiple access system, time-hopping (TH) spreading codes are a plausible choice to separate different users [4-6]. The time-reversal (TR)-based UWB scheme has been extensively investigated recently [7-9]. Attractive features of TR signal processing include: (1) It makes full use of the energy from all the resolvable paths. (2) The TR-based UWB technique shifts the sophisticated channel estimation burden from the mobile receivers to the transmitter at a fixed access point. Most past works of TR UWB scheme focus on the issue of single user transmission and detection, there has been surprising few contributions on the topic of multiuser TR UWB scheme.

This paper proposes a prefiltering-based transmission scheme for pulsed UWB system by shifting the signal processing needs from the receiver at the mobile unit to the transmitter at the basestation where power and computational resources are plentiful. We exploit antenna array in the basestation transmitter and take advantage of the spatial and temporal diversities to mitigate the MUI of a TH multiple access UWB communication system. The prefiltering scheme is developed to meet the zero-forcing (ZF) criterion. A simple correlation receiver is proposed at the mobile unit to combine the desired signal stemmed from all the transmitting antennas. The performances under different scenarios are extensively evaluated over multiple-input single-output (MISO) channels.

Notation: The boldface letters represent vector and matrix. $[\ ]^T$ stand for matrix or vector transpose. We will use $\|\ \|$ for vector norm, "*" for linear convolution operation. $\mathbf{e}_i$ is the *i*th column vector of an identity matrix. $\delta(\cdot)$ is the dirac delta function.

2. Signal and channel models

In UWB IR, every information symbol (bit) is conveyed by N_f data modulated ultra short pulses over N_f frames. There is only one pulse in each frame and the frame duration is T_f. The pulse waveform, $p(t)$, is referred to as a monocycle [1] with ultra-short duration T_c at the nano-second scale. The energy of $p(t)$ is normalized within T_c to unity, so that $\int_0^{T_c} |p(t)|^2\, dt = 1$. The binary (anti-podal) PAM scheme is considered, thus we may establish the data model of the *k*th transmitted signal as

$$s_k(t) = \sum_i a_k d_k(i) c_k(t) = \sum_i a_k d_k(i) \sum_{j=0}^{N_f-1} p\left(t - iN_f T_f - jT_f - c_j^k T_c\right) \tag{1}$$

where a_k is the amplitude of the *k*th user. The *i*th bit transmitted by *k*th user is given by $d_k(i)$, which takes on the value ± 1 with equal probability. $c_k(t) := \sum_{j=0}^{N_f-1} p\left(t - iN_f T_f - jT_f - c_j^k T_c\right)$ represents the specific periodic (with period $N_f T_f$) waveform assigned for the *k*th user. Denoting T_b as the bit duration, then

$T_b = N_f T_f$. Suppose each frame is composed of N_c time slots each with duration T_c , thus, $T_f = N_c T_c$. User separation is accomplished by user-specific pseudo-random TH code. $\left\{c_j^k\right\}_{j=0,\dots,N_f-1}$ accounts for the kth user's TH code with period N_f . Thereby $c_j^k T_c$ is the time-shift of the pulse position imposed by the TH sequence employed for multiple access. Note that to avoid the presence of intersymbol interference (ISI) in the system, we let the last frame for each user being empty (without pulse).

The channel impulse response (CIR) is formulated as

$$h(t) = \sum_{l=0}^{L} \alpha_l \delta\left(t - lT_c\right) \tag{2}$$

where we model the multipath channel as a tapped-delay line with $(L+1)$ taps. α_l denotes the tap weight of the lth resolvable path. The channel fading coefficient α_l can be modeled as [10]

$$\alpha_l = b_l \xi_l \tag{3}$$

where b_l is equiprobable to take on the value ± 1. $\xi_l = \left|\alpha_l\right|$ is the log-normal fading magnitude term.

3. Design of ZF UWB MISO system

As shown in Fig. 1, in the considered scheme, there are M transmitting antennas equipped at the basestation and each mobile user has single antenna. Let $h_{mk}\left(t\right) = \sum_{l=0}^{L} \alpha_{mk,l} \delta\left(t - lT_c\right)$ denotes the CIR between the mth transmitting antenna and the kth mobile receive. In the proposed prefiltering scheme, a set of prefilters with impulse response (IR) $\left\{g_{km}\left(t\right)\right\}_{\substack{k=1,\dots,K \\ m=1,\dots,M}}$ are inserted respectively between the kth signal and the mth transmitting antenna. The transmitted waveform at the mth antenna is

$$x_m(t) = \sum_{k=1}^{K} s_k(t) * g_{km}(t) \qquad ; m = 1, \dots, M \tag{4}$$

where K is the number of users. The received signal at the kth mobile receiver can be written as

$$\begin{aligned} r_k(t) &= \sum_{m=1}^{M} x_m(t) * h_{mk}(t) + n_k(t) = \sum_{m=1}^{M} \left(\sum_{j=1}^{K} s_j(t) * g_{jm}(t) \right) * h_{mk}(t) + n_k(t) \; ; k=1, \dots, K \\ &= \sum_{j=1}^{K} s_j(t) * \sum_{m=1}^{M} \left(g_{jm}(t) * h_{mk}(t) \right) + n_k(t) \end{aligned} \tag{5}$$

where $n_k(t)$ is assumed to be zero-mean AWGN noise process with variance σ^2. To avoid MUI, the MK zero-forcing prefilters, $\left\{g_{km}\left(t\right)\right\}_{\substack{k=1,\dots,K \\ m=1,\dots,M}}$, should be designed to satisfy the following criteria:

$$\sum_{m=1}^{M} \left(g_{jm}(t) * h_{mk}(t) \right) = \begin{cases} 0; \; j \neq k \\ \eta_k \delta\left(t - LT_c\right); \; j = k \end{cases} \qquad \forall j, k = 1, \dots, K \tag{6}$$

where the LT_c delay is introduced to accommodate the multipath effect. η_k accounts for the power normalization factor. Denoting the discrete-time version of the CIR as a $\left(L+1\right)$ vector $\mathbf{h}_{mk} := \left[\alpha_{mk,0} \quad \alpha_{mk,1} \quad \cdots \quad \alpha_{mk,L}\right]^T$, $g_{jm}\left(t\right) = \sum_{p=0}^{P-1} \beta_{jm,p} \delta\left(t - pT_c\right)$ as a P vector $\mathbf{g}_{jm} := \left[\beta_{jm,0} \quad \beta_{jm,1} \quad \dots \quad \beta_{jm,P-1}\right]^T$, respectively, then the discrete-time counterparts of $g_{jm}(t) * h_{mk}(t)$ can be obtained as

$$\mathbf{H}_{mk} \mathbf{g}_{jm} = \begin{bmatrix} \alpha_{mk,0} & 0 & \cdots & \cdots & 0 \\ \vdots & \alpha_{mk,0} & \ddots & \ddots & \vdots \\ \alpha_{mk,L} & \vdots & \ddots & \ddots & \vdots \\ 0 & \alpha_{mk,L} & \ddots & \ddots & 0 \\ \vdots & 0 & \ddots & \ddots & \alpha_{mk,0} \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & \alpha_{mk,L} \end{bmatrix} \begin{bmatrix} \beta_{jm,0} \\ \beta_{jm,1} \\ \vdots \\ \beta_{jm,P-1} \end{bmatrix} \tag{7}$$

In what follows, (6) can be converted into a convenient form

$$\mathbf{H}_k \mathbf{g}_j = \begin{cases} \mathbf{0}_{L+P}; \, j \neq k \\ \eta_k \mathbf{e}_L; \, j = k \end{cases} \tag{8}$$

where $\mathbf{H}_k := \begin{bmatrix} \mathbf{H}_{1k} & \mathbf{H}_{2k} & \cdots & \mathbf{H}_{Mk} \end{bmatrix}, \mathbf{g}_j := \begin{bmatrix} \mathbf{g}_{j1}^T & \mathbf{g}_{j2}^T & \cdots & \mathbf{g}_{jM}^T \end{bmatrix}^T$, $\mathbf{e}_L$ denotes the *L*th column vector of $\mathbf{I}_{(L+P)}$. $\mathbf{g}_j$ is a *MP* vector that incorporates the space-time impulse response of the *j*th user's prefilters. Rewriting (8) as

$$\mathbf{H}\mathbf{g}_k = \eta_k \mathbf{e}_{kL+(k-1)P} \tag{9}$$

where $\mathbf{H}$ is a $K(L+P) \times MP$ matrix and $\mathbf{e}_{kL+(k-1)P}$ denotes the $[kL+(k-1)P]$th column vector of $\mathbf{I}_{K(L+P)}$. If $K(L+P) \leq MP$, we have

$$\mathbf{g}_k = \eta_k \mathbf{H}^T \left(\mathbf{H}\mathbf{H}^T \right)^{-1} \mathbf{e}_{kL+(k-1)P} \tag{10}$$

To maintain the transmitted bit energy of the *k*th user to be $E_{b,k} = (N_f - 1) a_k^2$, we should let $\|\mathbf{g}_k\| = 1$. To achieve this $\eta_k = \frac{1}{\|\mathbf{g}_k\|}$. Substituting the above results into (6), we may rewrite the discrete-time version of the received signal within the *i*-th bit interval as

$$\mathbf{r}_k(i) = \eta_k a_k d_k(i) \mathbf{c}_{k,L} + \mathbf{n}_k(i) \tag{11}$$

where $\mathbf{c}_{k,L}$ stands for a *L*-chips delayed version of the *k*th user's TH code vector, $\mathbf{c}_k$. Since the MUI is completely removed, a simple correlation receiver, $\mathbf{c}_{k,L}$, can be employed that maximizes the averaged output signal-to-noise-power-ratio (SNR). The averaged output SNR can be obtained as

$$\gamma_k = \frac{\eta_k^2 a_k^2 \left(N_f - 1\right)^2}{\sigma^2 \left(N_f - 1\right)} = \frac{\eta_k^2 a_k^2 \left(N_f - 1\right)}{\sigma^2} \tag{12}$$

4. Performance evaluation

We first assume the average power of the path with index *l*=0 to be normalized to be unity, i.e., $\Omega_0 = 1$. The log-normal fading amplitude ξ_l is generated by $\xi_l = \exp(\kappa_l)$, where κ_l is a Gaussian random variable, $\kappa_l \sim N(\mu_l, \sigma_l^2)$. To satisfy the second moment of the log-normal random variable, we have $\mu_l = -\sigma_l^2 - \frac{\rho l}{2}$. For a fixed *L*, we generate 100 sets of channel parameters, $\{\alpha_{mk,l}\}_{l=0}^{L}$. Each data set is employed for simulation and the result is obtained by taking average of the 100 independent trials. Without loss of generality, we assume user 1 is the desired user hereafter. Unless otherwise mentioned, we set the parameters $N_c = N_f = 20$, *P*=20, *L*=15, *K*=10 and each user's SNR, which is defined as $SNR_k := 10 \log \left(\frac{a_k}{\sigma} \right)^2$, is set to be 15 dB throughout all the simulation examples. Fig. 2 presents γ_1 with respect to the number of transmitting antennas, *M*. As expected, the performance improves in accordance with *M*. This demonstrates that increasing the spatial diversity (*M*) enhance the averaged SNR. Fig. 3 measures the SNR performance with respect to prefilter length, P. We can observe from this figure that increase the temporal diversity effectively enhance system performance. γ_1 with respect to SNR_1 is shown in Fig.4. As expected, γ_1 increases in accordance with SNR_1.

5. Conclusions

A ZF-based prefiltering scheme has been applied in this paper to mitigate MUI in pulsed UWB system over MISO channel. The benefit of the proposed scheme is that it lessens the burden in signal processing of the mobile receiver where a simplified correlation receiver is typically required. The simulation results have demonstrated that the proposed scheme can effectively remove MUI and improve system performance by exploiting spatial and temporal diversity. Though binary (anti-podal) PAM scheme is considered in this paper, extension to PPM scheme is without conceptual difficulty.

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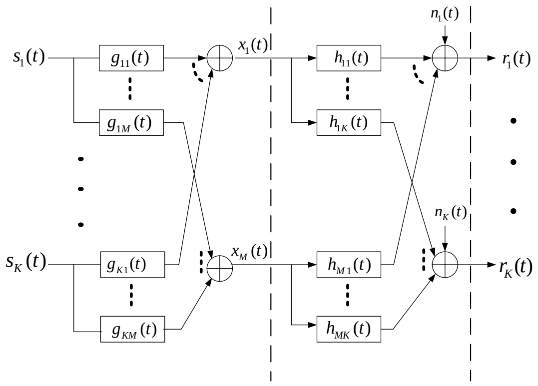

Fig. 1: Schematic block diagram of a prefiltering-based MISO UWB communication system.

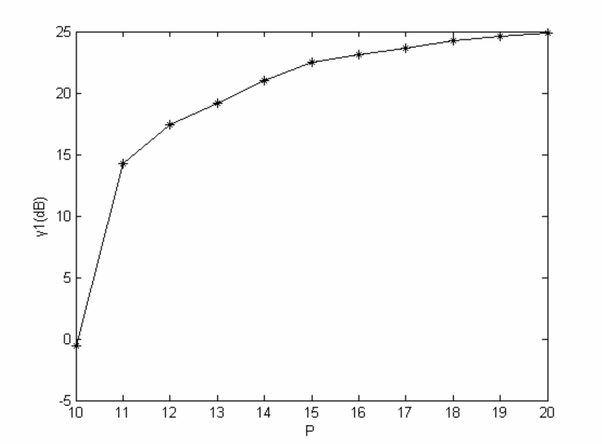

Fig. 3: γ_1 with respect to P.

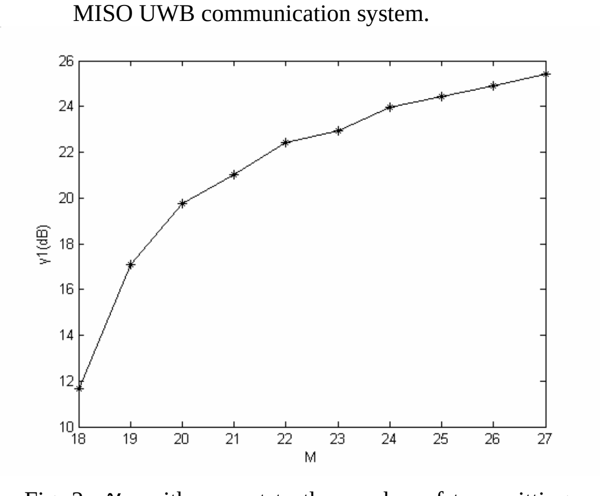

Fig. 2: γ_1 with respect to the number of transmitting antennas

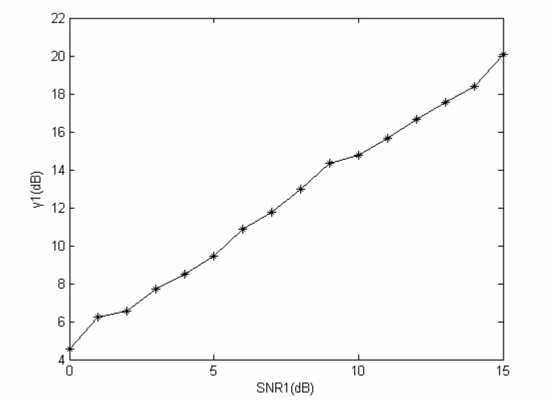

Fig. 4: γ_1 with respect to SNR_1