ICSP2008 Proceedings

A Preprocessing Algorithm of Ultra-wideband Signal for Space-Time Focusing Transmission

Zhongwei Liu Yafei Tian Chenyang Yang
School of Electronics and Information Engineering, Beihang University
E-mail: sdliuzhw@yahoo.com.cn, ytian@buaa.edu.cn, cyyang@buaa.edu.cn

Abstract

Ultra-wideband (UWB) signal has fine time resolution and can resolve a large amount of multipath in densely scattered environments. Exploiting these features, UWB systems can accomplish space-time focusing transmission. At the focused spot there will exhibit an energy peak, while in other places very weak interference will be induced. The space-time focusing transmission can not only enable the use of simple receiver structure, but also enhance the coexistence capability of UWB systems with the legacy narrowband systems. In this paper, a novel preprocessing method is proposed for multiuser UWB systems. By filtering the transmitted signal, the received signal at the focused time can be sampled without intersymbol interference and multiuser interference. Moreover, the interference to narrowband users can also be avoided.

1. Introduction

UWB communications provide a new way to share the spectrum, *i.e.* coexisting with the legacy narrow-band and wideband systems in an underlay mode[1], which enables the spectrum resources being utilized more efficiently. However, the strict spectral mask requirement of UWB signals considerably restricts its communication range and application scenarios.

Exploiting the fine time resolution, UWB systems can use a space-time focusing mode for signal transmission, which will dramatically improve the coexistence capability and enlarge the coverage range. In densely scattered environments, each reflector is a secondary radiation source. If the arrival time of the signal to each reflector is controlled appropriately, the multipath components can be summed up coherently and an energy peak can be created at the intended spot [2][3]. Since the correlation of the multipath channel response between different UWB links is quite low[4], the radios in other places will only be corrupted by weak interferences.

978-1-4244-2179-4/08/$25.00 ©2008 IEEE

Time reversal is a natural way to implement the space-time focusing transmission[5-7], which pre-filters the transmitted signal with the time reversed and phase conjugated version of the channel impulse response (CIR). However, the focusing capability of the time reversal technique relies on the raw auto- and cross-correlation of UWB channels, it can hardly inhibit the residual interference effectively[2].

In this paper, we propose a preprocessing method to enhance the space-time focusing capability of UWB systems. After passing through a single pre-filter, the transmitted signal not only will not cause intersymbol interference (ISI) to the intended UWB user, but also will not lead to multiuser interference (MUI) to other UWB users in the network. Moreover, it can avoid the band utilized by nearby narrowband users. The focusing transmission technique allows very simple receivers which only need to sample at the focused time, or just to do noncoherent detection. It implies that the complexity of the system is shifted from the receiver to the transmitter, which is very desirable in UWB networks that have a fixed access point (AP).

The rest of this paper is organized as follows. In the next section, the system model is described. In Section 3, we present the preprocessing algorithm for the space-time focusing transmission. The performance of the proposed scheme and the comparison with time reversal are illustrated in Section 4. The last section is conclusions.

2. System Model

Let us consider a centralized IR-UWB network that consists of an AP and K UWB users. In its working area, there are also a few narrowband users, whose operating frequency is within the frequency band of UWB signals.

Considering downlink transmission, the AP transmits signals to K users simultaneously. Using binary pulse amplitude modulation (BPAM), the amplitude of low duty-cycle short pulses is modulated by information bits. The transmitted signal of the k-th user without preprocessing is

$$s^{(k)}(t)=\sum_{n=0}^{N-1}\sqrt{E_b}x_n^{(k)}p(t-nT_b)\,, \tag{1}$$

where $p(t)$ is the UWB pulse of width T_w, E_b is the energy of each bit, T_b is the symbol duration, $x_n^{(k)}\in\{1,-1\}$ is the n-th information bit, and N is the number of bits or symbols in one packet. We assume that the symbol duration is integer folds of the pulse width, *i.e.* $M=T_b/T_w$.

Consider linear pre-filtering. Each user has its own pre-filter, and the pre-filer coefficients of the k-th user is $\mathbf{g}^{(k)}=\left[g_0^{(k)}\ g_1^{(k)}\ \cdots\ g_{L_m-1}^{(k)}\right]^T$. The pre-filter is normalized by its power.

After filtering, the transmitted signal of the k-th user is given by

$$s_p{}^{(k)}(t)=\sum_{n=0}^{N-1}\sqrt{E_b}x_n^{(k)}\sum_{l=0}^{L_m-1}g_l^{(k)}p(t-nT_b-lT_w)\,. \tag{2}$$

The signal that the AP transmits is the sum of K user's signals, which is

$$s(t)=\sum_{k=0}^{K-1}s_p{}^{(k)}(t)\,. \tag{3}$$

The channel can be modeled as a discrete linear filter, and the CIR between the AP and the k-th user can be expressed as

$$h^{(k)}(t)=\sum_{l=0}^{L_c-1}\alpha_l^{(k)}\delta(t-lT_w)\,, \tag{4}$$

where L_c is the number of resolvable paths, $\alpha_l^{(k)}$ is the channel fading coefficient for the l-th path. We assume that the number of pre-filter taps is equal to the number of resolvable paths, and both are equal to L.

The signal that the k-th user receives is

$$r^{(k)}(t)=s(t)*h^{(k)}(t)+z(t)\,, \tag{5}$$

where "$*$" denotes linear convolution, and $z(t)$ is the additive white Gaussian noise (AWGN).

3. The Preprocessing Method

3. 1 Preprocessing in the absent of ISI

Firstly, we consider that the symbol duration is large enough, so that no ISI exists. Assume that the AP knows the perfect CIR between the AP and all K users.

For each user, we take out the n-th symbol, and K symbols constitute a signal vector as follows

$$\mathbf{x}=[x_n{}^{(0)}\ x_n{}^{(1)}\ \cdots\ x_n{}^{(K-1)}]^T\,.$$

The signal vector is preprocessed, then transmitted. After passing through the UWB channel, the received signal vector can be obtained after synchronizing and sampling at the symbol rate, which is

$$\mathbf{y}=\mathbf{HGx}+\mathbf{z}\,, \tag{6}$$

where

$$\mathbf{y}=[y_n{}^{(0)}\ y_n{}^{(1)}\ \cdots\ y_n{}^{(K-1)}]^T\,,$$

$$\mathbf{G}=\begin{bmatrix} g_0^{(0)} & g_0^{(1)} & \cdots & g_0^{(K-1)} \\ \vdots & \vdots & & \vdots \\ g_{L-1}^{(0)} & g_{L-1}^{(1)} & \cdots & g_{L-1}^{(K-1)} \end{bmatrix} \tag{7}$$

is the pre-filter coefficient matrix,

$$\mathbf{H}=\begin{bmatrix} h_{L-1}^{(0)} & h_{L-2}^{(0)} & \cdots & h_1^{(0)} & h_0^{(0)} \\ \vdots & \vdots & & \vdots & \vdots \\ h_{L-1}^{(K-1)} & h_{L-2}^{(K-1)} & \cdots & h_1^{(K-1)} & h_0^{(K-1)} \end{bmatrix} \tag{8}$$

is the CIR matrix,

$$\mathbf{z}=[z_n{}^{(0)}\ z_n{}^{(1)}\ \cdots\ z_n{}^{(K-1)}]^T$$

is the noise vector with zero mean and covariance matrix $\sigma^2\mathbf{I}$, and $\mathbf{I}$ is the identity matrix.

It is desirable that each user does not interfere with each other. This requires

$$\mathbf{HG}=\mathbf{I}\,. \tag{9}$$

It follows from (9) that a natural criterion of designing pre-filter coefficients is zero forcing (ZF), which yields a pre-filter coefficient matrix as

$$\mathbf{G}_{ZF}=\mathbf{H}^H\cdot(\mathbf{H}\cdot\mathbf{H}^H)^{-1}\,, \tag{10}$$

where $(\cdot)^H$ denotes Hermitian transpose. When applying the minimum mean-square-error (MMSE) criterion, the pre-filter coefficient matrix can be obtained as

$$\mathbf{G}_{MMSE}=\mathbf{H}^H\cdot(\mathbf{H}\cdot\mathbf{H}^H+\sigma^2\mathbf{I})^{-1}\,. \tag{11}$$

3. 2 Preprocessing in the presence of ISI

Now we consider the case of $M=L/2$. Other cases with smaller M can be derived in the same way. When the transmitted signal goes through the channel, each symbol is corrupted by its previous and next symbols. Taking out three successive symbols of each user, we can form a vector as

$$\mathbf{x}'=[x_{n-1}^{(0)}\ x_n^{(0)}\ x_{n+1}^{(0)}\ x_{n-1}^{(1)}\ x_n^{(1)}\ x_{n+1}^{(1)}\ \cdots\ x_{n+1}^{(K-1)}]^T\,.$$

After synchronizing and sampling at the symbol rate, the received signal vector can be written as

$$\mathbf{y} = \mathbf{HG}'\mathbf{x}' + \mathbf{z}\,, \quad (12)$$

where

$$\mathbf{G}' = \begin{bmatrix} g_{L/2}^{(0)} & g_0^{(0)} & 0 & \cdots & g_{L/2}^{(K-1)} & g_0^{(K-1)} & 0 \\ \vdots & \vdots & \vdots & & \vdots & \vdots & \vdots \\ g_{L-1}^{(0)} & g_{L/2-1}^{(0)} & 0 & \cdots & g_{L-1}^{(K-1)} & g_{L/2-1}^{(K-1)} & 0 \\ 0 & g_{L/2}^{(0)} & g_0^{(0)} & \cdots & 0 & g_{L/2}^{(K-1)} & g_0^{(K-1)} \\ \vdots & \vdots & \vdots & & \vdots & \vdots & \vdots \\ 0 & g_{L-1}^{(0)} & g_{L/2-1}^{(0)} & \cdots & 0 & g_{L-1}^{(K-1)} & g_{L/2-1}^{(K-1)} \end{bmatrix}$$

is the pre-filter coefficient matrix.

In order to avoid both ISI and MUI, the coefficient matrix should satisfy following condition

$$\mathbf{HG}' = \begin{bmatrix} 0\;1\;0\;0\;0\;0\;\cdots 0\;0\;0 \\ 0\;0\;0\;0\;1\;0\;\cdots 0\;0\;0 \\ \cdots \qquad \cdots \\ 0\;0\;0\;0\;0\;0\;\cdots 0\;1\;0 \end{bmatrix}. \quad (13)$$

It is implied from (13) that there will be no ISI and MUI at the focused time, but the interference at other positions is not constrained.

The matrix $\mathbf{G}'$ cannot be solved directly from (13) given the CIR matrix $\mathbf{H}$, since the cyclic shifted structure of $\mathbf{G}'$ should be reserved. Thus we can transform (13) to an equivalent form

$$\mathbf{HG}' = \tilde{\mathbf{G}}'\tilde{\mathbf{H}}\,, \quad (14)$$

where

$$\tilde{\mathbf{H}} = \begin{bmatrix} h_{L/2}^{(0)} & h_0^{(0)} & 0 & \cdots & h_{L/2}^{(K-1)} & h_0^{(K-1)} & 0 \\ \vdots & \vdots & \vdots & & \vdots & \vdots & \vdots \\ h_{L-1}^{(0)} & h_{L/2-1}^{(0)} & 0 & \cdots & h_{L-1}^{(K-1)} & h_{L/2-1}^{(K-1)} & 0 \\ 0 & h_{L/2}^{(0)} & h_0^{(0)} & \cdots & 0 & h_{L/2}^{(K-1)} & h_0^{(K-1)} \\ \vdots & \vdots & \vdots & & \vdots & \vdots & \vdots \\ 0 & h_{L-1}^{(0)} & h_{L/2-1}^{(0)} & \cdots & 0 & h_{L-1}^{(K-1)} & h_{L/2-1}^{(K-1)} \end{bmatrix},$$

$$\tilde{\mathbf{G}}' = \begin{bmatrix} g_{L-1}^{(0)} & g_{L-2}^{(0)} & \cdots & g_1^{(0)} & g_0^{(0)} \\ \vdots & \vdots & & \vdots & \vdots \\ g_{L-1}^{(K-1)} & g_{L-2}^{(K-1)} & \cdots & g_1^{(K-1)} & g_0^{(K-1)} \end{bmatrix}.$$

Then we can obtain the ZF pre-filter as follows

$$\tilde{\mathbf{G}}'_{ZF} = (\tilde{\mathbf{H}}^H \cdot \tilde{\mathbf{H}})^{-1} \cdot \mathbf{H}_s^H\,, \quad (15)$$

where

$$\mathbf{H}_s = \begin{bmatrix} h_0^{(0)} & h_0^{(1)} & \cdots & h_0^{(K-1)} \\ \vdots & \vdots & & \vdots \\ h_{L-1}^{(0)} & h_{L-1}^{(1)} & \cdots & h_{L-1}^{(K-1)} \end{bmatrix}.$$

Considering the MMSE criterion, the pre-filter coefficient matrix can be obtained as

$$\tilde{\mathbf{G}}'_{MMSE} = (\tilde{\mathbf{H}}^H \cdot \tilde{\mathbf{H}} + \sigma^2\mathbf{I})^{-1} \cdot \mathbf{H}_s^H\,. \quad (16)$$

3. 3 Preprocessing in the presence of narrowband users

Narrowband users can be regarded as special UWB users, then the developed techniques can be applied directly to avoid the mutual interference. Without loss of generality, we consider that there is one nearby narrowband user whose operating frequency is f_0. This algorithm can be easily extended to the situation with multiple narrowband users. The narrowband signal experiences flat fading channel. Assume that the channel coefficient is α, then the CIR of the narrowband signal can be expressed as

$$\mathbf{h}_N = \alpha\left[e^{-jw_0(L-1)}\; e^{-jw_0(L-2)}\; \cdots\; e^{-jw_0 1}\; e^{-jw_0 0}\right],$$

where $w_0 = 2\pi f_0 / f_s$ is the digital frequency of the narrowband signal, and $f_s = 1/T_w$ is the sampling frequency of the pre-filter.

Taking the case without ISI as an example, we can add a row in (8) to reflect the contribution of the narrowband signal. Then the CIR matrix becomes $\overline{\mathbf{H}} = \left[\mathbf{H}\;\; \mathbf{h}_N\right]^T$. Because α is only a constant, we can drop it. Correspondingly, we add a column to (7), then the coefficient matrix becomes $\overline{\mathbf{G}} = \left[\mathbf{G}\quad \mathbf{g}^{(N)}\right]$, where $\mathbf{g}^{(N)}$ is the pre-filter coefficients for the narrowband signal. Since the AP does not really transmit a narrowband signal, a notch will occur at f_0 in the spectrum of UWB signal after such a preprocessing.

Applying the ZF criterion, the coefficient matrix is given by

$$\overline{\mathbf{G}}_{ZF} = \overline{\mathbf{H}}^H \cdot (\overline{\mathbf{H}} \cdot \overline{\mathbf{H}}^H)^{-1}\,, \quad (17)$$

where the first K columns of the matrix $\overline{\mathbf{G}}_{ZF}$ are the pre-filter coefficients of K UWB users.

4. Simulation Results and Discussion

In the simulations, the 2nd derivative Gaussian pulse with normalized energy is considered as the UWB pulse. The parameters are set as $T_w = 1\text{ns}$, $T_b = 15\text{ns}$ and $M = 15$. Assume that there are 4 UWB users in the network. We use the CM3 channel model with a root-mean-square (RMS) delay spread of 60ns and resolvable paths of 60 to evaluate the performance of the proposed method.

The transmit signal of the 1st UWB user is processed by the pre-filter $g^{(1)}(t)$, and then passes through the channel $h^{(1)}(t)$, so the equivalent channel response is given by $h_{11} = g^{(1)}(t) * h^{(1)}(t)$. Fig. 1 shows the impulse response of h_{11}. Note that there is a peak at time 0 of the CIR, and it contains 53.2% of the entire CIR's energy. Most of the signal energy is focused on this maximal path. Since $M = 15$, only the paths at time -45, -30, -15, 15, 30, 45 may induce ISI to signal at the path of time 0. But as shown in the figure, the values of the CIR at these time are approximate zero. This implies that the method we proposed can reduce the ISI significantly.

When the signal of the 2nd user arrives at the receiver of the 1st user, the impulse response of the equivalent channel is also shown in Fig. 1. Similarly, only the paths at time -45, -30, -15, 0, 15, 30, 45 cause MUI to the 1st user's signal at the path of time 0. But the values of the CIR at these time are approximate zero, so the MUI can also be reduced significantly.

In Fig. 2, we compare the bit error rate (BER) of time reversal and the presented preprocessing method. It is shown that there is an error floor at 10^{-2} when using time reversal. The performance of the presented preprocessing method is much better than that of time reversal, and when applying MMSE criterion, there is only 3dB performance loss at 10^{-5} comparing to the performance in AWGN.

If there is a nearby narrowband user whose operating frequency is 200MHz, by using the designed pre-filter, there will be a notch in the spectrum of UWB signal. Fig. 3 shows the result (marked by a circle). We can see that the -10dB bandwidth of the notch is about 4MHz. Therefore, the interference to the narrowband user can be almost completely avoided.

5. Conclusions

In this paper, we proposed a preprocessing method for space-time focusing transmission. Simulation results show that this method can reduce the ISI and MUI significantly, and can offer much better focusing capability than the time reversal technique. The proposed scheme allows a very simple and low cost receiver with only a single tap, which is very desirable in centralized UWB networks. Moreover, the interference to narrowband users can also be effectively controlled.

6. References

[1] M. E. Sahin, S. Ahmed, and H. Arslan, "The roles of ultra wideband in cognitive networks," in Proc. IEEE International Conf. on Ultra-Wideband, pp. 247-252, Sept. 2007.

[2] T. Strohmer, M. Emami, J. Hansen, G. Papanicolaou, and P. J. Arogyaswami, "Application of time-reversal with MMSE equalizer to UWB communications," in Proc. IEEE Global Telecommunications Conf., vol. 5, pp. 3123–3127, Dec. 2004.

[3] J. Karedal. et al.," UWB channel measurements in an industrial environment," in Proc. IEEE Global Telecommunications Conf. , vol. 5, pp. 3511– 3516, Dec. 2004.

[4] C. Oestges, A. D. Kim, G. Papanicolaeou, A. J. Paulraj, "Characterization of space-time focusing in time-reversed random fields," IEEE Trans. on Antennas and Propagation, vol. 53, pp. 283-293, Jan. 2005.

[5] H. T. Nguyen, J. B. Andersen, and G. F. Pedersen, "The potential use of time reversal techniques in multiple element antenna systems," IEEE Communications Letters, vol. 9, pp. 40-42, Jan. 2005.

[6] H. T. Nguyen, I. Z. Kovcs, and P. C. F. Eggers, "A time reversal transmission approach for multiuser UWB communications," IEEE Trans. on Antennas and Propagation, vol. 54, pp. 3216-3224, Nov. 2006.

[7] R. C. Qiu, C. Zhou, N. Guo, and J. Q. Zhang, "Time reversal with MISO for ultra-wideband communications: experimental results," IEEE Antennas and Wireless Propagation Letters, vol. 5, pp. 269-273, Dec. 2006.

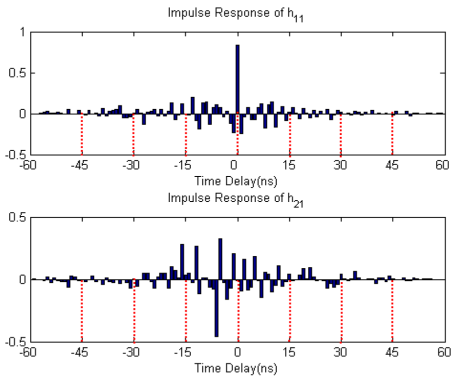

Fig. 1. Impulse response of h_{11} and h_{21}

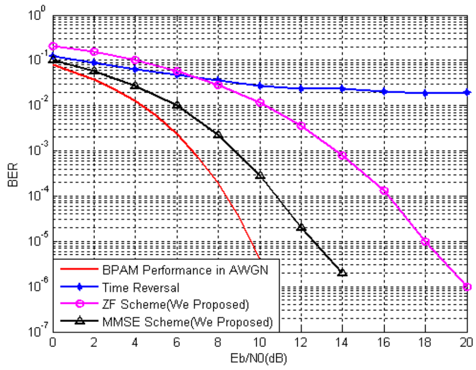

Fig. 2. BER performance in CM3

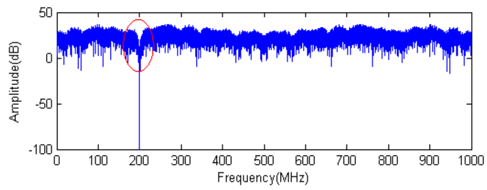

Fig. 3. Spectrum of the filtered UWB signal