Application of SVD on Suppression of IEEE 802.11a Interference in TH-PAM UWB Systems

Shaoyi Xu, Zhiquan Bai, Qinghai Yang, and Kyung Sup Kwak

ABSTRACT— Interference from IEEE 802.11a systems affects ultra-wideband (UWB) systems significantly. In this letter, we suggest a novel narrow-band interference (NBI) suppression technique based on the singular value decomposition (SVD) algorithm in time-hopping pulse amplitude modulation (TH-PAM) UWB systems. The SVD algorithm is used to approximate the interference which then is subtracted from the received signals. In contrast to the conventional notch filter and rake receiver, our method is more effective and the receiver complexity can be greatly reduced.

Keywords—SVD, NBI, TH-PAM UWB.

I. Introduction

The IEEE 802.11a systems operate at around 5 GHz overlapping the band of ultra-wideband (UWB) signals regulated by the FCC, which leads to significant interference in UWB systems. Interference suppression techniques for IEEE 802.11a systems have received very little attention so far. In this letter, we present a novel approach based on the singular value decomposition (SVD) algorithm to suppress IEEE 802.11a signals for time-hopping pulse amplitude modulation (TH-PAM) UWB systems. The SVD is used to estimate this narrow-band interference (NBI) which then is subtracted from the received signals. We also include the conventional notch filter and the maximal-ratio combining partial rake (MRC PRake) receiver for comparison. Simulation results confirm that our method effectively suppresses NBI and greatly reduces receiver complexity.

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Shaoyi Xu (phone: +82 32 8648935, email: shaoyixu@hotmail.com), Zhiquan Bai (email: sdzqbai@hotmail.com), Qinghai Yang (email: yangqing_hai@hotmail.com), and Kyung Sup Kwak (email: kskwak@inha.ac.kr) are with the Department of Information Technology and Telecommunications, Inha University, Incheon, Korea.

II. System Model

The transmitted signal in a single-user TH-BPAM UWB system can be described by

$$s(t)=\sum_{j=iN_s}^{(i+1)N_s-1} d_i w_{tr}(t-jT_f-C_jT_c), \qquad (1)$$

where $w_{tr}(t)$ is the transmitted pulse with the duration of T_p, T_f is the frame duration, C_j is the j-th code of a PN sequence, T_c is the chip duration, N_s is the number of pulses required to transmit a single bit, and $d_i \in \{\pm 1\}$ is the i-th transmitted bit. Let $h(t)=\sum_{l=1}^{L}\alpha_l\delta(t-\tau_l)$ denote the multipath channel with L paths, and let α_l and τ_l denote, respectively, the channel attenuation and time delay of the l-th path which we can use to define two vectors $\boldsymbol{\alpha}=[\alpha_1,\alpha_2,\cdots,\alpha_L]^T$ and $\boldsymbol{\tau}=[\tau_1,\tau_2,\cdots,\tau_L]^T$. The received signal can be expressed as

$$r(t)=\sum_{j=iN_s}^{(i+1)N_s-1}\sum_{l=1}^{L}\alpha_l d_i w_{rx}(t-jT_f-C_jT_c-\tau_l)+i(t)+n(t), \qquad (2)$$

where $w_{rx}(t)$ is the received pulse at the output of the antenna, $i(t)$ is the NBI signal, and $n(t)$ is the additive white Gaussian noise (AWGN) with two-sided power spectral density $N_0/2$. We use an MRC PRake which exploits the first L_p paths out of L available diversity paths and combines them according to MRC which employs the weighs vector $\boldsymbol{\beta}=\boldsymbol{\alpha}$. The template waveform for the l-th correlator with the time delay τ_l of the j-th frame is given by

$$\phi_l^j(t)=w_{rx}(t-jT_f-C_jT_c-\tau_l), \qquad (3)$$

giving the output $r_l(t)=\sum_{j=0}^{N_s-1}\int_{(j-1)T_f}^{jT_f} r(t)\phi_l^j(t)dt$, which can be denoted by a vector as $\mathbf{r}=[r_1,r_2,\cdots,r_L]^T$. Therefore, the rake output can be expressed as $Y=\boldsymbol{\alpha}^T\mathbf{r}=\sum_{l=1}^{L_p}\alpha_l r_l(t)$.

As given in [1], the IEEE 802.11a systems employ orthogonal frequency division multiplexing (OFDM)-based transmission as:

$$i(t)=\mathrm{Re}\left(\sum_{k=-\frac{N_{ST}}{2}}^{\frac{N_{ST}}{2}-1} a_k e^{j2\pi k\Delta F(t-T_G)} e^{j2\pi f_c t}\right), \tag{4}$$

where N_{ST} is the number of subcarriers, a_k is the transmitted OFDM data, T_G and ΔF represent the guard time and subcarrier frequency spacing, respectively, f_c is the carrier frequency, and Re(X) denotes the real part of X.

III. NBI Suppression Algorithm and Effect

Sampled according to [2], for the time series $r(n)$, $n=1, 2, \cdots, N$, we can construct a Hankel matrix with $M=N-L+1$ rows and L columns illustrated as follows:

$$\mathbf{R}=\begin{bmatrix} r(1) & r(2) & \cdots & r(L) \\ r(2) & r(3) & \cdots & r(L+1) \\ \vdots & \vdots & & \vdots \\ r(N-L+1) & r(N-L+2) & \cdots & r(N) \end{bmatrix}. \tag{5}$$

Using the SVD, $\mathbf{R}$ can be factorized as $\mathbf{R}=\mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^H$ where $\mathbf{U}(M\times M)$ and $\mathbf{V}(L\times L)$ are unitary matrices. The nonnegative entries of the diagonal matrix $\boldsymbol{\Sigma}=diag(\sigma_1,\sigma_2,\cdots,\sigma_m)$ are the singular values of $\mathbf{R}$, and they are square roots of the eigenvalues of $\mathbf{R}^H\mathbf{R}$ or $\mathbf{R}\mathbf{R}^H$. These singular values are arranged in decreasing order with the largest one in the upper left-hand corner.

With the characteristic of white noise, in the absence of high-energy NBI, the UWB signal has similar singular values which are all close to zero. After high NBI is introduced to the UWB system, there will be several dominant singular values to represent such interference [3]. In this case, $\mathbf{R}$ is the superposition of the UWB signal space and noise space which can be expressed as

$$\begin{aligned}\mathbf{R}=\mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^H&=[\mathbf{U}_R\ \ \mathbf{U}_S]\begin{bmatrix}\boldsymbol{\Sigma}_R & 0\\ 0 & \boldsymbol{\Sigma}_S\end{bmatrix}[\mathbf{V}_R\ \ \mathbf{V}_S]^H \\ &=\mathbf{U}_R\boldsymbol{\Sigma}_R\mathbf{V}_R^H+\mathbf{U}_S\boldsymbol{\Sigma}_S\mathbf{V}_S^H=\mathbf{R}_R+\mathbf{R}_S,\end{aligned} \tag{6}$$

where $\boldsymbol{\Sigma}_R=diag(\sigma_1,\sigma_2,\cdots,\sigma_k)$ and $\boldsymbol{\Sigma}_S=diag(\sigma_{k+1},\sigma_{k+2},\cdots,\sigma_m)$ with $\sigma_1>\sigma_2>\cdots>\sigma_k>>\sigma_{k+1}>\sigma_{k+2}>\cdots>\sigma_m$ correspond to the singular values in the interference subspace $\mathbf{R}_R$ and the data subspace $\mathbf{R}_S$, respectively. Subtracting $\mathbf{R}_R$ from $\mathbf{R}$, we can get the estimated data matrix $\mathbf{R}_S$ with suppressed NBI. The SVD-based technique can be summarized as follows.

Step 1. Choose L so that $k<L<N-k$ [3] and arrange the received signal vector to form a Hankel data matrix $\mathbf{R}$.

Step 2. Compute the SVD of $\mathbf{R}$. Then, obtain the approximated interference subspace $\mathbf{R}_R$.

Step 3. Subtract $\mathbf{R}_R$ from $\mathbf{R}$ to obtain $\mathbf{R}_S$ and rearrange it into the time series $\tilde{r}(n)$ to perform detection in the receiver.

Substituting (2), (3), and (4) into the form of $r_l(t)$ yields $r_l(t)=z_l(t)+i_l(t)+n_l(t)$, where

$$z_l(t)=N_s d_i \alpha_l \int_{(j-1)T_f}^{jT_f} w_{rx}^2(t)dt=N_s d_i \alpha_l E_w, \tag{7}$$

$$\begin{aligned}i_l(t)=A_i\sum_{j=0}^{N_s-1}\sum_{k=-\frac{N_{ST}}{2}}^{\frac{N_{ST}}{2}-1}\mathrm{Re}\Big\{a_k e^{j2\pi(k\Delta F+f_c)(jT_f+C_jT_c+\tau_l-D_i)}e^{-j2\pi k\Delta FT_G}\\ \cdot\int_{(j-1)T_f}^{jT_f} w_{rx}(t)e^{j2\pi(k\Delta F+f_c)t}dt\Big\}, \text{ and}\end{aligned} \tag{8}$$

$$n_l(t)=\sum_{j=0}^{N_s-1}\int_{(j-1)T_f}^{jT_f} n(t)w_{rx}(t-jT_f-C_jT_c-\tau_l)dt, \tag{9}$$

which respectively denote the UWB signal, NBI, and the noise component at the output of the l-th correlator. The amplitude attenuation and the time shift of the received OFDM signals are denoted by A_i and D_i, and $n_l(t)$ is a zero-mean Gaussian random variable with variance $E_wN_0N_s/2$, where $E_w=\int_{(j-1)T_f}^{jT_f} w_{rx}^2(t)dt$. Thus, we can obtain the output of the MRC PRake receiver as

$$Y=\sum_{l=1}^{L_p}\alpha_l(z_l(t)+i_l(t)+n_l(t))=\boldsymbol{\alpha}^T(\mathbf{z}+\mathbf{i}+\mathbf{n}), \tag{10}$$

where $\mathbf{z}=[z_1,z_2,\cdots,z_{L_p}]^T$, $\mathbf{i}=[i_1,i_2,\cdots,i_{L_p}]^T$, and $\mathbf{n}=[n_1,n_1,\cdots,n_{L_p}]^T$. Hence, the signal to interference and noise ratio (SINR) is

$$SINR=\frac{(N_sE_w)^2\left|\boldsymbol{\alpha}^T\boldsymbol{\alpha}\right|^2}{\boldsymbol{\alpha}^T\mathbf{R}_i\boldsymbol{\alpha}+\boldsymbol{\alpha}^T\mathbf{R}_n\boldsymbol{\alpha}}, \tag{11}$$

where $\mathbf{R}_i=E\{\mathbf{i}\mathbf{i}^H\}$ and $\mathbf{R}_n=E\{\mathbf{n}\mathbf{n}^H\}$ are the correlation matrices of NBI and AWGN, respectively.

Let $\mathbf{R}_S=\mathbf{U}_S\boldsymbol{\Sigma}_S\mathbf{V}_S^H$ and $\tilde{\mathbf{R}}_S=\tilde{\mathbf{U}}_S\tilde{\boldsymbol{\Sigma}}_S\tilde{\mathbf{V}}_S^H$ respectively denote the SVD of the received data matrix without NBI and the received data matrix with NBI suppressed by the proposed method. Therefore, the mean-squared error (MSE) is

$$\begin{aligned}\delta_{SVD}^2&=\left\|\mathbf{R}_S-\tilde{\mathbf{R}}_S\right\|^2=trace\left[(\mathbf{R}_S-\tilde{\mathbf{R}}_S)(\mathbf{R}_S-\tilde{\mathbf{R}}_S)^H\right]\\ &=trace\Big[\mathbf{U}_S\boldsymbol{\Sigma}_S^2\mathbf{U}_S^H-\mathbf{U}_S\boldsymbol{\Sigma}_S\mathbf{V}_S^H\tilde{\mathbf{V}}_S\tilde{\boldsymbol{\Sigma}}_S\tilde{\mathbf{U}}_S^H\\ &\quad-\tilde{\mathbf{U}}_S\tilde{\boldsymbol{\Sigma}}_S\tilde{\mathbf{V}}_S^H\mathbf{V}_S\boldsymbol{\Sigma}_S\mathbf{U}_S^H+\tilde{\mathbf{U}}_S\tilde{\boldsymbol{\Sigma}}_S^2\tilde{\mathbf{U}}_S^H\Big].\end{aligned} \tag{12}$$

On the assumption that $\mathbf{U}_S \approx \widetilde{\mathbf{U}}_S$ and $\mathbf{V}_S \approx \widetilde{\mathbf{V}}_S$, the MSE of SVD can be approximated by $\delta_{SVD}^2 \approx \Sigma_{i=1}^{k} \sigma_i^2 < k\sigma_{\max}^2$, where σ_i is the singular value of $\mathbf{R}_S$ and $\sigma_{\max}$ is the maximum among them. From the above analysis we can observe that $\widetilde{\mathbf{R}}_S$ is the best least squares approximation of $\mathbf{R}_S$.

IV. Simulation Results and Discussion

We adopt two IEEE UWB multipath channel models (CM1 with LOS and CM3 with NLOS) [2]. At the transmitter, the second derivative of the Gaussian pulse is used as the transmitted UWB monocycle. The transmitted UWB signal is modulated as N_p=25, T_p=1 ns, T_c=2 ns, and T_f=50 ns. We utilize the whole 7.5 GHz frequency band of UWB signals. The OFDM signal is generated as N_{ST}=52, f_c=5.22 GHz, T_G=0.8 μs, and ΔF=0.3125 MHz [1]. When the SVD algorithm is used, the receiver is a 3-finger MRC PRake receiver. Satisfying $k<L<N-k$, we choose $L=N/5$.

In Figs. 1 and 2, we compare our algorithm with the 3-finger and 10-finger MRC PRake in the CM1 and CM3 models, respectively, when the signal to NBI ratio (SIR) = –30 dB, –20 dB and –10 dB. As expected, the NBI is greatly mitigated by using our technique. By using our method, only a 3-finger MRC PRake is enough to suppress such strong NBI so that the complexity of the receiver can be decreased dramatically.

Figure 3 shows the performance of our method and the notch filter with a 3-finger MRC PRake receiver in the CM1 model. The notch filter is a Chebyshev II IIR bandstop filter with a passband ripple of 1 dB and a stopband attenuation of 40 dB. We can observe clearly that our method outperforms the notch filter.

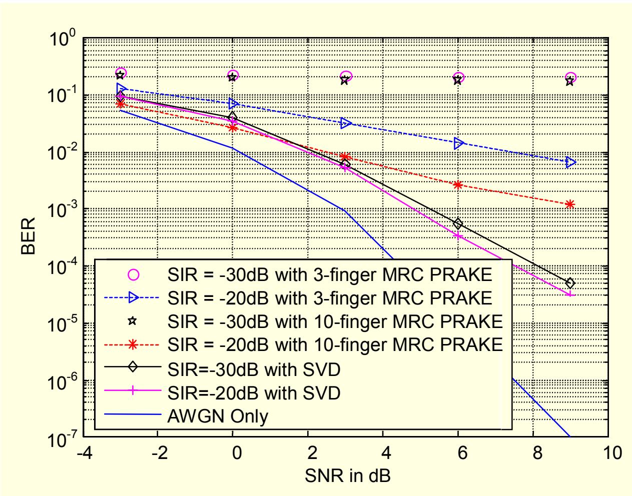

Fig. 1. SVD method and rake receiver in CM1 model.

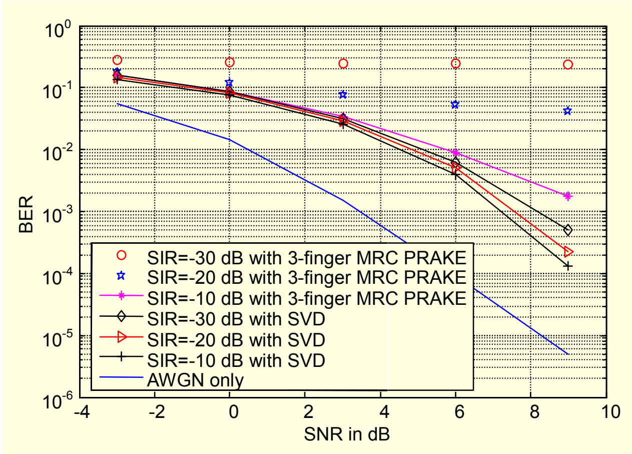

Fig. 2. SVD method and rake receiver in CM3 model.

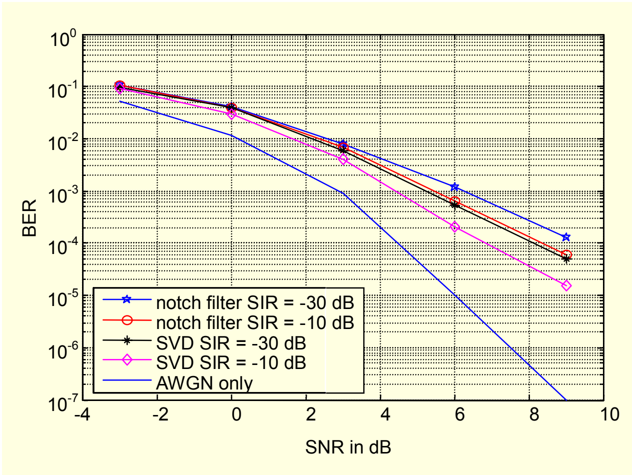

Fig. 3. SVD method and notch filter in CM1 model.

V. Conclusion

An SVD-based algorithm to suppress IEEE 802.11a signal interference for TH-PAM UWB systems has been presented. Our algorithm is effective and receiver complexity can be greatly reduced.

References

[1] B. Firoozbakhsh, T. G. Pratt, and N. Jayant, "Analysis of IEEE 802.11a Interference on UWB Systems," *Proc. IEEE Conf. on Ultra Wideband Systems and Technologies*, Reston, USA, Nov. 2003, pp. 473-477.

[2] IEEE P802.15 Working Group for WPAN, *Channel Modeling Sub-Committee Report Final*, IEEE P802.15-02/368rSG3a, 2002.

[3] D.W. Tufts and R. Kumaresan, "Singular Value Decomposition and Improved Frequency Estimation Using Linear Prediction," *IEEE Trans. Signal Proc.*, vol. 30, no. 4, 1982, pp. 671- 675.