Journal of Zhejiang University SCIENCE A
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Multipurpose audio watermarking algorithm

Ning CHEN[†], Jie ZHU
(*Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*)
[†]E-mail: chenning_750210@163.com

Received Sept. 17, 2007; revision accepted Jan. 16, 2008; published online Mar. 13, 2008

Abstract: To make audio watermarking accomplish both copyright protection and content authentication with localization, a novel multipurpose audio watermarking scheme is proposed in this paper. The zero-watermarking idea is introduced into the design of robust watermarking algorithm to ensure the transparency and to avoid the interference between the robust watermark and the semi-fragile watermark. The property of natural audio that the VQ indices of DWT-DCT coefficients among neighboring frames tend to be very similar is utilized to extract essential feature from the host audio, which is then used for watermark extraction. And, the chaotic mapping based semi-fragile watermark is embedded in the detail wavelet coefficients based on the instantaneous mixing model of the independent component analysis (ICA) system. Both the robust and semi-fragile watermarks can be extracted blindly and the semi-fragile watermarking algorithm can localize the tampering accurately. Simulation results demonstrate the effectiveness of our algorithm in terms of transparency, security, robustness and tampering localization ability.

Key words: Multipurpose audio watermarking, Copyright protection, Content authentication
doi:10.1631/jzus.A071493 **Document code:** A **CLC number:** TP309

INTRODUCTION

Digital watermarking has been proposed to accomplish copyright protection or content authentication. However, in some application domains, one might wish to embed several watermarks in the same signal to accomplish different goals. For example, the owner might desire to: use one watermark to convey ownership information, use a second watermark to verify content integrity, and use a third watermark to convey a caption (Mintzer and Braudaway, 1999). In order to fulfill multipurpose applications, several image multipurpose watermarking algorithms have been presented (Ji *et al*., 2003; Lu *et al*., 2005; 2006; Xiong *et al*., 2006; Yuan *et al*., 2006). In (Ji *et al*., 2003), a scheme based on chaotic sequences is proposed. The massive and independent digital watermark signals are generated trough 1D chaotic maps, which are determined by different initial conditions and parameters. Each watermark is added to the middle frequency coefficients of wavelet domain randomly by exploiting 2D chaotic system, so that the embedding and extracting of each watermark do not disturb with each other. In (Lu *et al*., 2005), an image multipurpose watermarking method based on the multistage vector quantizer structure is presented, in which the semi-fragile watermark (for content authentication) and the robust watermark (for copyright protection) are embedded in different VQ stages using different techniques, and both of them can be extracted without the original image. Since the human auditory system (HAS) is extremely more sensitive than human visual system (HVS), multipurpose audio watermarking provides a special challenge when compared with the development of multipurpose image watermarking (Wang *et al*., 2004). Up to now, few multipurpose audio watermarking schemes have been presented. A cocktail watermarking scheme for audio signal is described in (Lu *et al*., 2000), where different detection procedures are utilized to detect robust watermark and semi-fragile watermark and the tampering localization is also achieved. However, its robustness against commonly used audio signal processing manipulations is not satisfactory. In (Wang *et al*., 2005), the robust watermark is embedded in the low frequency range using mean quantization, while the semi-fragile watermark is embedded in the high frequency range by quantizing single coefficient. Both the robust watermark and the semi-fragile watermark can be extracted without host audio. But, the semi-fragile watermarking scheme can not achieve tampering localization. A wavelet domain multipurpose audio watermarking scheme based on blind source separation (BSS) is given in (Ding, 2006), where the semi-fragile watermark can give the authentication result as well as the tampered area. However, the embedding of robust watermark in the coarse wavelet coefficients affects the transparency greatly.

The technical challenges existing in the design of multipurpose audio watermarking schemes include: (1) How to reduce the effect of the latter embedded watermarks on the former embedded one? (2) How to solve the conflict between robustness and transparency? (3) How to realize the independent and blind extraction of each watermark? (4) How to make the whole scheme robust against commonly used audio signal processing manipulations? In order to solve these problems, a novel multipurpose audio watermarking scheme is presented in this paper. In the proposed scheme, a chaotic mapping based semi-fragile watermark (for content authentication with tampering localization) is embedded in the detail wavelet coefficients based on the instantaneous mixing model of the independent component analysis (ICA) scheme, while a robust watermark (for copyright protection) is embedded based on the zero-watermarking idea (Cao *et al*., 2006; Sang *et al*., 2006; Li and Liu, 2007).

VECTOR QUANTIZATION AND INDEPENDENT COMPONENT ANALYSIS

Vector quantization

Vector quantization is defined as a mapping from the k-dimensional Euclidean space $\mathbb{R}^k$ into a finite codebook $B=\{\boldsymbol{b}_i|i=0,1,\ldots,L_B-1\}$, where $\boldsymbol{b}_i$ is a codeword and L_B is the codebook size. The VQ encoder searches the nearest codeword to represent each input vector $\boldsymbol{v}$ according to the least distortion criterion as follows:

$$d(\boldsymbol{v},\boldsymbol{b}_i)=\min_{0\le j\le L_B-1} d(\boldsymbol{v},\boldsymbol{b}_j), \tag{1}$$

where $d(\boldsymbol{v}, \boldsymbol{b}_j)$ is the distortion between the input vector $\boldsymbol{v}$ and the codeword $\boldsymbol{b}_j$, and it can be calculated as follows:

$$d(\boldsymbol{v},\boldsymbol{b}_j)=\sum_{l=0}^{k-1}(v_l-b_{jl})^2. \tag{2}$$

Compression is achieved by transmitting the codeword index i rather than the codeword itself. In the decoding process, the VQ decoder performs the table look-up operation to find the codeword $\boldsymbol{b}_i$ that is used to reconstruct the input vector $\boldsymbol{v}$.

Independent component analysis

ICA (Ma *et al*., 2006) is a very general-purpose statistical technique to recover the independent sources given only sensor observations that are linear mixtures of independent source signals. Suppose that there exist P mutually independent source signals $\boldsymbol{s}_1,\boldsymbol{s}_2,\ldots,\boldsymbol{s}_P$, and Q observed mixtures $\boldsymbol{x}_1,\boldsymbol{x}_2,\ldots,\boldsymbol{x}_Q$ of the source signals (usually $Q\ge P$), the model of ICA can be represented as

$$\boldsymbol{x}=\boldsymbol{A}\boldsymbol{s}, \tag{3}$$

where $\boldsymbol{s}=[\boldsymbol{s}_1,\boldsymbol{s}_2,\ldots,\boldsymbol{s}_P]^{\mathrm{T}}$ and $\boldsymbol{x}=[\boldsymbol{x}_1,\boldsymbol{x}_2,\ldots,\boldsymbol{x}_Q]^{\mathrm{T}}$ represent the source signals vector and observed vector respectively, and $\boldsymbol{A}$ is a $Q\times P$ scalar mixing matrix of full rank. ICA is to estimate the source signal $\boldsymbol{s}$ or a de-mixing matrix $\boldsymbol{V}$ only from the observed signal $\boldsymbol{x}$ according to the statistical characteristic of $\boldsymbol{s}$. Then the source signals are recovered:

$$\tilde{\boldsymbol{s}}=\boldsymbol{V}\boldsymbol{x}=\boldsymbol{V}\boldsymbol{A}\boldsymbol{s}, \tag{4}$$

where $\tilde{\boldsymbol{s}}$ is the estimation of source signals vector.

PROPOSED SCHEME

Semi-fragile watermark embedding process

The semi-fragile watermark will be embedded in the detail wavelet coefficients of the host audio signal. First, perform m-level wavelet decomposition on the host audio signal to get the detail coefficients $c\boldsymbol{D}^m$; Next, perform n-level wavelet decomposition on $c\boldsymbol{D}^m$ to get its coarse coefficients $c\boldsymbol{D}^m\boldsymbol{A}^n$; then, generate a chaotic mapping based semi-fragile watermark sequence with the same size of $c\boldsymbol{D}^m\boldsymbol{A}^n$; finally, embed the watermark in $c\boldsymbol{D}^m\boldsymbol{A}^n$ based on the instantaneous mixing model of ICA scheme (Fig.1).

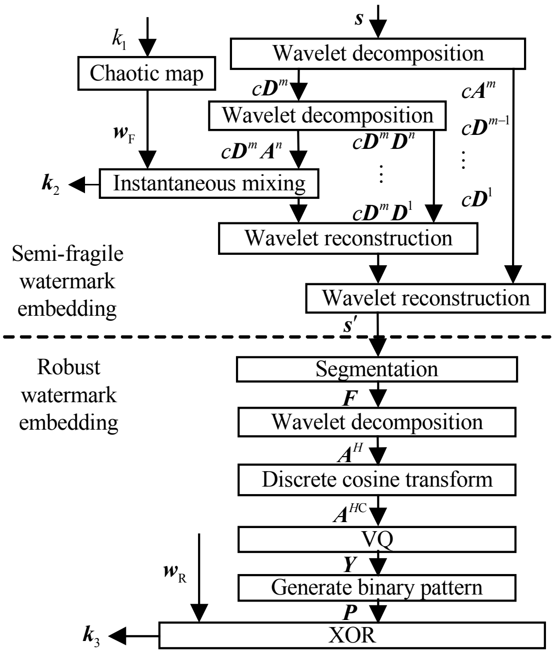

Fig.1 Watermark embedding process

The specific procedures are as follows:

(1) Perform m-level wavelet decomposition on the host audio $\boldsymbol{s}$ to get the coarse coefficients $c\boldsymbol{A}^m$ and detail coefficients $c\boldsymbol{D}^m,\ldots,c\boldsymbol{D}^1$; and then perform n-level wavelet decomposition on $c\boldsymbol{D}^m$ to get its coarse coefficients $c\boldsymbol{D}^m\boldsymbol{A}^n$, denoted as $\boldsymbol{s}_1=\{s_1(i)|i=1,\ldots,L_F\}$, and detail coefficients $c\boldsymbol{D}^m\boldsymbol{D}^n,\ldots,c\boldsymbol{D}^m\boldsymbol{D}^1$.

(2) Generate a chaotic sequence $\boldsymbol{c}=\{c(i)|i=1,\ldots,L_F\}$ based on logistic map [Eq.(5)] with the initial value $k_1\in(0, 1)$,

$$c(i+1)=3.6\cdot c(i)[1-c(i)], \tag{5}$$

and map $\boldsymbol{c}$ into a semi-fragile watermark $\boldsymbol{w}_F=\{w_F(i)|i=1,\ldots,L_F\}$ with

$$w_F(i)=\begin{cases}-1, & \text{if } c(i)\geq 0.5,\\ 1, & \text{else.}\end{cases} \tag{6}$$

(3) Embed $\boldsymbol{w}_F$ into the wavelet coefficients $\boldsymbol{s}_1$ based on the instantaneous mixing model of ICA as follows:

$$\boldsymbol{X}=\begin{pmatrix}\boldsymbol{x}_1\\ \boldsymbol{x}_2\end{pmatrix}=\boldsymbol{AS}=\begin{pmatrix}a_{11} & a_{12}\\ a_{21} & a_{22}\end{pmatrix}\begin{pmatrix}\boldsymbol{s}_1\\ \boldsymbol{w}_F\end{pmatrix}, \tag{7}$$

where $\boldsymbol{A}$ is the mixing matrix. To ensure the transparency, we make $a_{11}>>a_{12}$, $a_{21}>>a_{22}$. And, when the values of a_{11} and a_{21} are fixed, the increasing of the values of a_{12} and a_{22} will lead to the increase of robustness and the decrease of transparency.

(4) Replace $\boldsymbol{s}_1$ with $\boldsymbol{x}_1$. Perform two-stage wavelet reconstruction with $\boldsymbol{x}_1$ and the other wavelet coefficients $c\boldsymbol{D}^m\boldsymbol{D}^n,\ldots,c\boldsymbol{D}^m\boldsymbol{D}^1,c\boldsymbol{A}^m,c\boldsymbol{D}^{m-1},\ldots,c\boldsymbol{D}^1$ to get the watermarked audio signal $\boldsymbol{s}'$. And keep $\boldsymbol{x}_2$ as the secret key $\boldsymbol{k}_2$ for watermark extraction.

Robust watermark embedding process

For natural audio signal, the VQ indices of DWT-DCT coefficients among neighboring frames tend to be very similar, so we make use of this property to generate a polarity $\boldsymbol{P}$. Then the robust watermark is embedded in the secret key by performing exclusive-or (XOR) operation between the polarity $\boldsymbol{P}$ and the watermark.

Let $\boldsymbol{w}_R$ be the robust watermark, which is a binary-valued image of size $M\cdot N$. The specific embedding procedures can be described as follows:

(1) Segment $\boldsymbol{s}'$ into $M\cdot N$ equal frames, denoted as $\boldsymbol{F}=\{\boldsymbol{f}(i)|i=1,\ldots,M\cdot N\}$.

(2) Perform H-level wavelet decomposition on each frame $\boldsymbol{f}(i)$ to get its coarse signal $\boldsymbol{A}_i^H$ and detail signals $\boldsymbol{D}_i^H$, $\boldsymbol{D}_i^{H-1}$, $\cdots$, $\boldsymbol{D}_i^1$. To take advantage of low frequency coefficient which has a high energy value and robust against various signal processing manipulations, the DCT is only performed on $\boldsymbol{A}_i^H$ to get $\boldsymbol{A}_i^{HC}$.

$$\boldsymbol{A}_i^{HC}=DCT(\boldsymbol{A}_i^H). \tag{8}$$

(3) Perform LBG algorithms (Gersho and Gray, 1992) on $\boldsymbol{A}^{HC}=\{\boldsymbol{A}_i^{HC}|i=1,\ldots,M\cdot N\}$ to get an L-level codebook $CB=\{\boldsymbol{cb}_1,\ldots,\boldsymbol{cb}_L\}$ and then perform VQ on $\boldsymbol{A}^{HC}$ to get the indices vector $\boldsymbol{Y}$:

$$\boldsymbol{Y}=VQ(\boldsymbol{A}^{HC})=\bigcup_{i=1}^{M\cdot N}VQ(\boldsymbol{A}_i^{HC})=\bigcup_{i=1}^{M\cdot N}y(i). \tag{9}$$

(4) Generate a polarity $\boldsymbol{P}$ as follows. First, calculate the variance of $y(i)$ and its surrounding indices with

$$\sigma^2(i)=\frac{1}{3}\sum_{q=i-1}^{q=i+1} y^2(q)-\left(\frac{1}{3}\sum_{q=i-1}^{q=i+1} y(q)\right)^2. \qquad (10)$$

Then, generate a polarity $\boldsymbol{P}$ based on $\sigma^2(i)$ with

$$\boldsymbol{P}=\bigcup_{i=1}^{M\cdot N} p(i), \qquad (11)$$

$$p(i)=\begin{cases}1, & \text{if } \sigma^2(i)\geq \underset{i}{median}[\sigma^2(i)],\\ 0, & \text{otherwise.}\end{cases} \qquad (12)$$

(5) Perform XOR operation on $\boldsymbol{w}_{\mathrm{R}}$ and $\boldsymbol{P}$ to get the secret key $\boldsymbol{k}_3=\{k_3(l)|l=1,\ldots,M\cdot N\}$. And

$$k_3(l)=w_{\mathrm{R}}(i,j)\oplus p(l), \quad l=N(i-1)+j. \qquad (13)$$

Finally, to prevent the attackers from embedding another watermark in the same host audio signal and claiming the copyright, the host audio, the secret keys and the corresponding digital timestamp should be registered or associated with an authentication center for copyright demonstration.

In the watermarking detection procedure, first generate a polarity $\boldsymbol{P}'$ from the test audio $\hat{\boldsymbol{s}}$, and then get the estimated robust watermark, denoted as $\hat{\boldsymbol{w}}_{\mathrm{R}}$, by performing XOR operation between $\boldsymbol{P}'$ and $\boldsymbol{k}_3$. See Fig.2.

Semi-fragile watermark extraction process

The semi-fragile watermark can be extracted as follows (Fig.2).

(1) Perform two-stage wavelet decomposition on the test audio $\hat{\boldsymbol{s}}$ to get the wavelet coefficients $\boldsymbol{cD}^m(\boldsymbol{A}^n)'$, denoted as $\boldsymbol{s}_1'$.

(2) Generate the mixture observations $\hat{\boldsymbol{X}}$ as

$$\hat{\boldsymbol{X}}=\begin{pmatrix}\boldsymbol{s}_1'\\ \boldsymbol{k}_2\end{pmatrix}, \qquad (14)$$

and perform the FastICA algorithm (Hyvarinen, 1999) on $\hat{\boldsymbol{X}}$ to get the estimated semi-fragile watermark $\hat{\boldsymbol{w}}_{\mathrm{F}}$.

(3) Calculate the cross-correlation coefficients λ between $\hat{\boldsymbol{w}}_{\mathrm{F}}$ and the original semi-fragile watermark $\boldsymbol{w}_{\mathrm{F}}$, which is obtained by performing Eqs.(5) and (6) on the secret key k_1.

$$\lambda=\frac{\sum_{i=1}^{L_{\mathrm{F}}} w_{\mathrm{F}}(i)\cdot \hat{w}_{\mathrm{F}}(i)}{\left[\sum_{i=1}^{L_{\mathrm{F}}}\left|w_{\mathrm{F}}(i)\right|^2\cdot\sum_{i=1}^{L_{\mathrm{F}}}\left|\hat{w}_{\mathrm{F}}(i)\right|^2\right]^{1/2}}. \qquad (15)$$

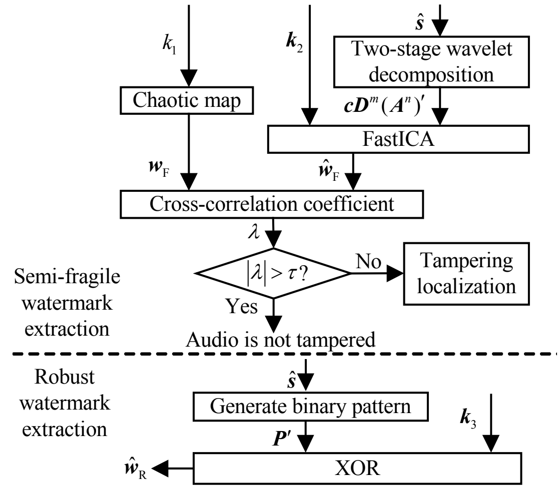

Fig.2 Watermark extraction process

Then, the subsequent work can be classified into two types according to the value of λ:

(1) $|\lambda|\geq\tau$, where τ is a predetermined threshold (The decreasing of τ will lead to the increase of false-alarm probability and the decrease of false dismissal probability). In this case, we believe that the test audio was secure and there is no tampering existing in it.

(2) $|\lambda|<\tau$. In this case, we believe that the test audio has been tampered with and the next step is to localize the tampering. First replace all the wavelet coefficients generated in two-stage wavelet decomposition, except for $\boldsymbol{cD}^m(\boldsymbol{A}^n)'$, with zero vectors of corresponding length and then perform two-stage wavelet reconstruction on them. Thus, the tampering can be localized accurately in the time domain. Now, let us see an example. Fig.3a shows a piece of speech signal with embedded semi-fragile watermark. To test the tampering localization performance of the proposed semi-fragile watermarking algorithm, the watermarked speech is tampered with as follows: (1) The samples from 1 to 21 500 are set to zero; (2) The samples from 205 000 to 228 000 are replaced with the samples of another speech signal. Then, the tampered speech signal and the tampering localization result are shown in Figs.3b and 3c, respectively.

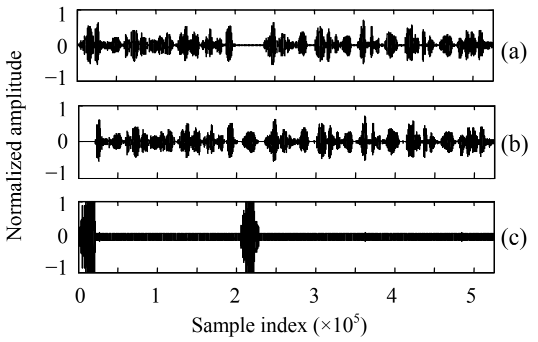

Fig.3 Tampering localization test results of the speech signal. (a) Watermarked speech; (b) Tampered watermarked speech; (c) Tampering localization result

SIMULATION RESULTS AND ANALYSIS

A piece of music and a piece of speech of 524288 samples, with 16 bits signed and sampled at 44.1 kHz were taken as the host audios. The parameter values used in this study were: $M=N=64$, $m=3$, $n=2$, $H=4$, $L=8$, $a_{11}=0.99$, $a_{12}=0.01$, $a_{21}=0.98$, $a_{22}=0.02$, $\tau=0.9$. Furthermore, the signal-to-noise ratio (SNR) and the normalized cross-correlation (NC) were employed to measure the transparency and robustness of the proposed scheme, respectively:

$$SNR(\boldsymbol{s},\boldsymbol{s}')=10\cdot\lg\left(\sum_{i=1}^{L_s}s^2(i)\Big/\sum_{i=1}^{L_s}\left(s(i)-s'(i)\right)^2\right), \quad (16)$$

$$NC(\boldsymbol{w}_{\mathrm{R}},\hat{\boldsymbol{w}}_{\mathrm{R}})=\frac{\sum_{i=1}^{M}\sum_{j=1}^{N}w_{\mathrm{R}}(i,j)\cdot\hat{w}_{\mathrm{R}}(i,j)}{\sqrt{\sum_{i=1}^{M}\sum_{j=1}^{N}w_{\mathrm{R}}^2(i,j)}\cdot\sqrt{\sum_{i=1}^{M}\sum_{j=1}^{N}\hat{w}_{\mathrm{R}}^2(i,j)}}, \quad (17)$$

where L_s is the length of $\boldsymbol{s}$.

Transparency test

The SNR between the original host music (resp. speech) and the watermarked music (resp. speech) was 40.4434 dB (resp. 33.8065 dB). It was difficult for human ear to distinguish between them. To verify the stability of transparency, the transparency test was performed on another 200 pieces of music signals and speech signals. The results shown in Fig.4 verify that the proposed scheme has good and stable transparency.

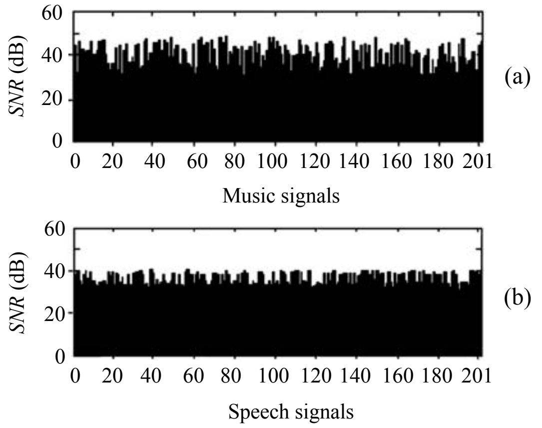

Fig.4 Transparency test results of 201 pieces of signals. (a) Test results of music signals; (b) Test results of speech signals

Security test

To test the security of the proposed scheme, we attempted to extract the watermarks from non-watermarked audio signals with the keys needed for extracting $\boldsymbol{w}_{\mathrm{R}}$ and $\boldsymbol{w}_{\mathrm{F}}$ from the watermarked audio signal. In addition to the watermarked music (watermarked speech), another 200 pieces of music signals (speech signals) without watermarks were used in this study. The test results, including *NC* and cross-correlation coefficients, are shown in Figs.5 and 6 for music signals and speech signals, respectively. The peaks in these figures correspond to the watermarked music and watermarked speech. Namely, the proposed technique can correctly extract watermarks from the matched audio and keys, while avoiding false watermark estimation from the unmatched audios, so it achieves great security.

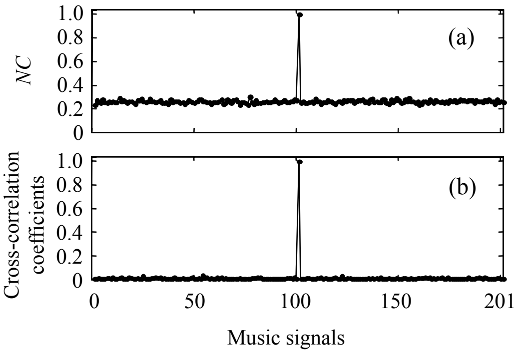

Fig.5 Security test results of 201 music signals. (a) Robust watermarking security; (b) Semi-fragile watermarking security

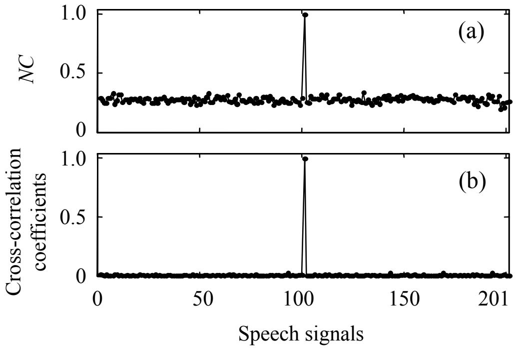

Fig.6 Security test results of 201 speech signals. (a) Robust watermarking security; (b) Semi-fragile watermarking security

Robustness test

The audio signal processing manipulations shown in Table 1 were performed on the watermarked audio signals, and then the watermarks were extracted again. The simulation results ($|\lambda|$ and *NC*) summarized in Table 1 and the extracted robust watermarks shown in Fig.7 verify that both the robust and semi-fragile watermarking algorithms have certain robustness against audio signal processing manipulations. Furthermore, the robustness of the proposed robust watermarking algorithm against the attacks provided by practical audio watermarking evaluation tool "Stirmark for Audio v0.2" was compared with that of the scheme proposed in (Wang and Zhao, 2006). The comparison results summarized in Table 2 indicate that the performance of our method is better than that of the scheme proposed by Wang and Zhao (2006).

Tampering localization test

The tampering localization test result shown in Fig.3 indicates that the adopted semi-fragile watermarking can localize the tampering accurately. To test the effects of signal processing manipulations on the tampering localization results, the manipulations shown in Table 1 were performed on the watermarked audio signals and the tampered ones, and then the tampering localization test was performed again. The results shown in Fig.8 indicate that the tampering localization has certain robustness against audio signal processing manipulations.

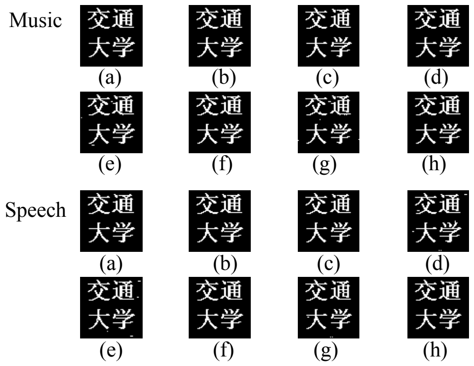

Fig.7 Extracted robust watermarks under commonly used audio signal processing manipulations. The descriptions of (a)~(h) are given in Table 1

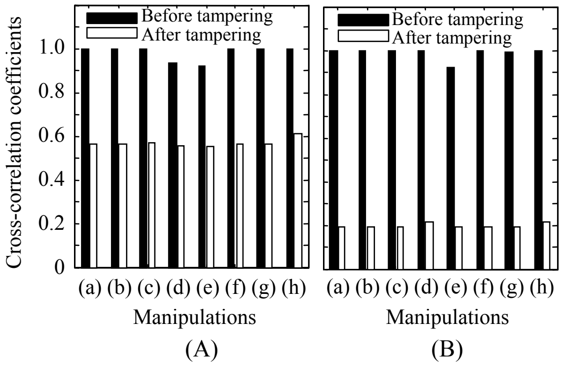

Fig.8 Tampering localization under commonly used audio signal processing manipulations. (A) Results for speech signal; (B) Results for music signal

Table 1 Robustness against commonly used audio signal processing manipulations

Manipulations	$\lvert\lambda\rvert$		*NC*	
	Music	Speech	Music	Speech
(a) Without attack	1.0000	1.0000	1.0000	1.0000
(b) MP3 (48 kbps)	1.0000	1.0000	1.0000	1.0000
(c) Low-pass filtering (22.05 kHz)	1.0000	1.0000	1.0000	1.0000
(d) Re-quantizing (16→8→16 bits/sample)	0.9983	0.9328	1.0000	0.9906
(e) White noise (2 dB)	0.9230	0.9215	0.9931	0.9897
(f) Delaying (500 ms, 10%)	1.0000	1.0000	1.0000	1.0000
(g) Echo addition (500 ms, 10%)	0.9959	0.9990	0.9897	0.9948
(h) Resampling (22.05→44.1→22.05 kHz)	0.9983	1.0000	1.0000	1.0000

λ: cross-correlation coefficient; *NC*: normalized cross-correlation

Table 2 Comparison of robustness against attacks provided by "Stirmark for Audio v02"

Attacks	Music		Speech	
	Ours	Wang's	Ours	Wang's
addnoise_900	0.7630	0.5208	0.9301	0.8909
addsinus	0.9055	0.7084	0.7316	0.8821
compressor	0.7295	0.2689	0.9940	0.5553
fft_real_reverse	0.9797	0.9856	1.0000	0.9991
zero_cross	0.9739	0.9905	0.8830	0.4200
smooth	0.9716	0.3475	0.9957	0.9991
smooth2	0.8995	0.3378	0.9948	0.9389
stat1	0.9492	0.3181	0.9285	0.4200
stat2	0.9941	0.9023	0.9974	1.0000

CONCLUSION AND FUTURE WORK

A novel multipurpose audio watermarking scheme is proposed in this paper. The robust and semi-fragile watermarks are embedded in the host audio simultaneously to provide copyright protection as well as content authentication with localization for it. Compared with available multipurpose audio watermarking algorithms, the advantages of the proposed algorithm include: (1) The robust watermark and the semi-fragile watermark can be embedded without considering embedding order and be extracted independently; (2) Both the robust and semi-fragile watermarking achieve satisfactory security; (3) Both the robust and the semi-fragile watermarking have certain robustness against audio signal processing manipulations; (4) The semi-fragile watermarking can localize tampering accurately. However, there are still some issues that deserve further exploration: (1) The semi-fragile watermarking algorithm cannot tell what kind of tampering the watermarked audio suffers from; (2) The psychoacoustic model is not adopted in the proposed scheme.

References

Cao, H.Q., Xiang, H., Li, X.T., Liu, M., Yi, S., Wei, F., 2006. A Zero-Watermarking Algorithm Based on DWT and Chaotic Modulation. Proc. SPIE, **6247**:624716-1-624716-9. [doi:10.1117/12.663927]

Ding, X.Y., 2006. Study on the Digital Audio Watermarking Scheme Based on Blind Source Separation. MS Thesis, School of Electronic and Information Engineering, Dalian University of Technology, p.26-35 (in Chinese).

Gersho, A., Gray, R.M., 1992. Vector Quantization and Signal Compression. Kluwer Academic Publishers, Boston.

Hyvarinen, A., 1999. Fast and robust fixed-point algorithms for independent component analysis. *IEEE Trans. on Neural Networks*, **10**(3):626-634. [doi:10.1109/72.761722]

Ji, Z., Xiao, W.W., Wang, J.H., Zhang, J.H., 2003. A multiple watermarking algorithm for digital image based on chaotic sequences. *Chin. J. Computers*, **26**(11):1555-1561 (in Chinese).

Li, J., Liu, F.L., 2007. Double Zero-Watermarks Scheme Utilizing Scale Invariant Feature Transform and Log-polar Mapping. Proc. IEEE Int. Conf. on Multimedia and Expo, p.2118-2121.

Lu, C.S., Mark Liao, H.Y., Chen, L.H., 2000. Multipurpose Audio Watermarking. Proc. 15th Int. Conf. on Pattern Recognition, p.282-285.

Lu, Z.M., Xu, D.G., Sun, S.H., 2005. Multipurpose image watermarking algorithm based on multistage vector quantization. *IEEE Trans. on Image Processing*, **14**(6): 822-831. [doi:10.1109/TIP.2005.847324]

Lu, Z.M., Zheng, W.M., Pan, J.S., Sun, Z., 2006. Multipurpose image watermarking method based on mean-removed vector quantization. *J. Inf. Assur. Secur.*, **1**(1):33-42.

Ma, X.H., Liang, Z.J., Yin, F.L., 2006. A Digital Audio Watermarking Scheme Based on Independent Component Analysis and Singular Value Decomposition. Proc. Fifth Int. Conf. on Machine Learning and Cybernetics, p.2434-2438. [doi:10.1109/ICMLC.2006.258775]

Mintzer, F., Braudaway, G.W., 1999. If One Watermark Is Good, Are More Better? Proc. IEEE Int. Conf. on Acoustics, Speech, and Signal Processing, **4**:2067-2069.

Sang, J., Liao, X.F., Alam, M.S., 2006. Neural-network-based zero-watermark scheme for digital images. *Opt. Eng.*, **45**(9):097006-1-097006-9. [doi:10.1117/1.2354076]

Wang, R.D., Xu, D.W., Li, Q., 2005. Multiple Audio Watermarks Based on Lifting Wavelet Transform. Proc. IEEE Int. Conf. on Machine Learning and Cybernetics, p.1959-1964. [doi:10.1109/ICMLC.2005.1527266]

Wang, X.Y., Zhao, H., 2006. A novel synchronization invariant audio watermarking scheme based on DWT and DCT. *IEEE Trans. on Signal Processing*, **54**(12):4835-4840. [doi:10.1109/TSP.2006.881258]

Wang, X.Y., Cui, Y.R., Yang, H.Y., Zhao, H., 2004. A New Content-based Digital Audio Watermarking Algorithm for Copyright Protection. Proc. Third Int. Conf. on Information Security, **85**:62-68.

Xiong, S.H., Zhou, J.L., He, K., Lang, F.N., 2006. A Multipurpose Image Watermarking Method Based on Adaptive Quantization of Wavelet Coefficients. Proc. First Int. Multi-Symp. on Computer and Computational Sciences, **1**:294-297. [doi:10.1109/IMSCCS.2006.14]

Yuan, J., Cui, G.H., Zhang, Y.J., 2006. A Practical Multipurpose Color Image Watermarking Algorithm for Copyright Protection and Image Authentication. Proc. Int. Conf. on Digital Telecommunications, p.72-75. [doi:10.1109/ICDT.2006.10]