DIGITAL WATERMARKING OF NATURAL IMAGES BASED ON LPTV FILTERS

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ABSTRACT

In this paper, Linear Periodically Time Varying (LPTV) filters are used as an alternative to direct sequence modulation in spread spectrum watermarking techniques. Due to their periodicity, LPTV filters combined with a Peano-Hilbert scan in the spatial domain of natural images offer good decoding performance. Specific LPTV filters are proposed to reject the low-pass host noise and to shape the watermark spectrum. Extensions to improved spread spectrum and quantization in a subspace projection are also investigated.

Index Terms— Image processing, Spread spectrum communication

1. INTRODUCTION

Digital watermarking consists of embedding data at the content-level of digital media under the constraints of imperceptibility, security and robustness to attacks. Its applications range from digital rights management to integrity protection. In Direct Sequence (DS) Spread Spectrum watermarking, the additive mark is the secret message modulated by a pseudo-noise. The message is detected by correlation with this pseudo-noise. Classical spread spectrum methods are subject to host interference. Extensions provide improved performance thanks to Wiener prefiltering before detection (DS+W) or optimal decoding for a given host image statistical model [1]. Informed watermarking provides better performance since in this case, the embedding uses knowledge upon both the host image and the detection technique [2]. For instance, Linear Improved Spread Spectrum (LISS) [3] is a modulation technique that removes the signal as source of interference. Recent advances focus on random binning inspired from Costa's work in information theory. In practice, a reasonably large but suboptimal binning codebook can be constructed using quantization. In Spread Transform Scalar Costa Scheme (ST-SCS) [4], robustness to noise is improved by quantizing the projection of the data onto a pseudo-random vector.

Linear Periodically Time Varying (LPTV) filters [5] have been applied in telecommunications to interleaving, blind equalization and spread spectrum communications [6][7]. Besides, many watermarking schemes rely on the analogy between watermarking and telecommunications with side information. A simple implementation of LPTV filters called Periodic Clock Changes (PCC) has been applied to watermarking in [8]. PCCs, that can be considered as a secret pulse position modulation technique, have been shown to exhibit similar performance as DS modulation in the case of Additive White Gaussian noise (AWGN) attack and host signal. Moreover, they allow to exploit the correlation of natural image samples to increase robustness. The application of more powerful LPTV filters to digital watermarking had never been investigated.

The following notations will be used: let $\mathbf{m}$ denote the original message of size L. Let $\mathbf{b}$ denote the coded message, $\mathbf{x}$ the original document, $\mathbf{w}$ the watermark, $\mathbf{y} = \mathbf{x}+\mathbf{w}$ the watermarked document, $\mathbf{n}$ the attack noise and $\mathbf{z}$ the received document, all of size N. Let $P = N/L$ denote the redundancy. Elements of any vector $\mathbf{a}$ will be denoted a_k. Let define $\sigma_{\mathbf{a}}^2$ the variance of any element of $\mathbf{a}$. Let define the Document to Watermark Ratio (DWR) and the Watermark to Noise Ratio (WNR):

$$\text{DWR} \triangleq \frac{\sigma_{\mathbf{x}}^2}{\sigma_{\mathbf{w}}^2},\ \text{WNR} \triangleq \frac{\sigma_{\mathbf{w}}^2}{\sigma_{\mathbf{n}}^2}$$

Simulations present the average performance on a test image set composed of Lena, Baboon, Fishingboat, Pentagon and Peppers.

Section 2 of this paper introduces two families of invertible LPTV filters inspired from telecommunications. In Section 3, an application to blind digital watermarking is proposed. LPTV filters are also applied to two informed watermarking techniques inspired from LISS and ST-SCS. In Section 4, specific LPTV filters are designed for watermarking of natural images. Finally, the robustness of the proposed techniques is studied in Section 5.

2. LPTV FILTERS INSPIRED FROM TELECOMMUNICATIONS

2.1. Definitions

An LPTV filter $\mathcal{F}$ is a filter whose impulse response $h(n,k)$ is a periodic function of the time. Let T denote this period, $\mathbf{u}$ the input of the filter and $\mathbf{v}$ its output ($\mathbf{v} = \mathcal{F}(\mathbf{u})$). Then

$$v_k = \sum_{k=-\infty}^{+\infty} h(n,k) u_{n-k}, \qquad h(n+T,k) = h(n,k) \ . \quad (1)$$

The transfer function $H_n(\omega)$ is defined by

$$H_n(\omega) = \sum_{k=-\infty}^{+\infty} h(n,k) e^{-ik\omega}, \qquad H_n(\omega) = H_{n+T}(\omega) \quad (2)$$

A PCC is a particular case of LPTV filter where f is a T-periodic permutation and $H_n(\omega) = e^{-if(n)\omega}$.

Let $U(\omega)$, $V(\omega)$ the respective Fourier transforms of $\mathbf{u}$ and $\mathbf{v}$, and $U(z)$, $V(z)$ their Z transforms. Two decompositions of LPTV filters will be used in the following [5]. The so-called polyphase decomposition of a signal $\mathbf{u}$ is

$$[u_{kT+i}] \to U_i(z) \triangleq \sum_{k=-\infty}^{\infty} u_{kT+i} z^{kT+i} \quad (3)$$

If both $\mathbf{u}$ and $\mathbf{v}$ are decomposed in polyphase components, an LPTV filter has the following Multiple Input-Multiple Output (MIMO) formulation:

$$[V_i(z)] = [H_{i,j}(z)][U_j(z)] \quad (4)$$

The input modulator decomposition consists of defining T Linear Time Invariant (LTI) filters $\mathrm{Tm}_k(\omega)$:

$$V(\omega) = \sum_{k=0}^{T-1} \mathrm{Tm}_k(\omega) U(\omega - \frac{2\pi}{T} k) \quad (5)$$

Equation (5) states that the output spectrum of an LPTV filter is the sum of shifted, weighted copies of the input spectrum. Thus, LPTV filters naturally spread, without necessarily whitening, the spectrum of input signals. While the MIMO decomposition provides an easy implementation, the modulator decomposition is useful to design LPTV filters with specific spectral properties.

2.2. LossLess LPTV filters (LL-LPTV)

LossLess LPTV (LL-LPTV) filters have been proposed and applied to telecommunications in [7]. LL-LPTV filters are inspired from perfect reconstruction filter banks, that achieve reconstruction of an input signal without amplitude or phase distortion [9]. Let A a "lossless" (stable and unitary) TxT random matrix used in the polyphase domain. Let $C_i, i = 1, \dots, p$ random vectors that introduce delays:

$$H(z) = H_p(z) \dots H_1(z) A \quad \text{with} \quad H_i(z) = (I - z^{-1}) C_i \quad (6)$$

For simplicity, the case $p = 0$ will be considered in the following. In this case, (4) leads to $[V_i(z)] = A[U_j(z)]$. The lossless matrix of the inverse LPTV filter is simply the transconjugate of A.

2.3. Constant modulators LPTV filters (mod-LPTV)

Another method for the construction of invertible LPTV filters has been proposed in [10] and is based on piecewise constant modulators. To our knowledge, this technique has not been applied yet to telecommunications. Let A a TxT matrix. The proposed LPTV filters are defined by $\mathrm{Tm}_{k-l}(\omega) = a(k,l)$ for $\frac{\omega}{2\pi} \in [\frac{k}{T} - \frac{1}{2}, \frac{k+1}{T} - \frac{1}{2}]$. Equation (5) becomes:

$$V(\omega) = \sum_{l=0}^{T-1} a(k, k-l) U(\omega - \frac{2\pi}{T} l) \quad (7)$$

Let V_k and U_k denote the regions of $V(f)$ and $U(f)$ with $\frac{\omega}{2\pi} \in [\frac{k}{T} - \frac{1}{2}, \frac{k+1}{T} - \frac{1}{2}]$. Then (7) is equivalent to

$$V_k = \sum_{l=0}^{T-1} a(k,l) U_l \quad (8)$$

Thus, the filter corresponds to several matrix operations $V = AU$ in the spectral domain. The invertibility of A is sufficient to construct an invertible LPTV filter with $U = A^{-1}V$. For simplicity, only real-valued orthogonal matrices A have been considered in this paper. As in [10], invertible LPTV filters with particular spatial properties can be designed with the same technique by introducing delays of the form $Ce^{i\omega c}$ in A. A multi-user extension of mod-LPTV is possible thanks to a sufficient condition derived in [6].

3. WATERMARKING SCHEMES BASED ON LPTV

3.1. Blind spread spectrum embedding

In this paper, we propose to spread the spectrum of the coded message **b** by an LPTV filter. In the basic blind embedding technique, the additive watermark **w** is directly the spreaded message. At the decoding, the inverse LPTV filter is applied to the attacked document in order to compute an estimation $\hat{\mathbf{b}}$ of **b**. Here, the host document **x** plays the role of noise at the decoding:

$$\mathbf{y} = \mathbf{x} + \mathcal{F}(\mathbf{b}) \quad \text{and} \quad \hat{\mathbf{b}} = \mathcal{F}^{-1}(\mathbf{z}) \quad (9)$$

This scheme is applied in this paper to LL-LPTV and mod-LPTV, with **b** obtained by repetition coding.

3.2. Theoretical performance facing AWGN

The performance of LL-LPTV and mod-LPTV at the detection and decoding are similar to that of DS if the sources of noise **x** and **n** are assumed to be AWGN. Indeed, the filter being linear, their contribution at the decoding can be studied independently. For LL-LPTV, $\sigma_{\mathbf{v}}^2 = \sum_{k=0}^{T-1} |a(k,l)|^2 \sigma_{\mathbf{u}}^2 = \sigma_{\mathbf{u}}^2$ since A is orthogonal. Let S_u and S_v the respective power spectrum densities of $\mathbf{u}$ and $\mathbf{v}$. For mod-LPTV, the same result is derived from the following equation [11]:

$$S_v(\omega) = \sum_{k=0}^{T-1} |\mathrm{Tm}_k(\omega)|^2 S_u(\omega - \frac{2\pi}{T} k) \quad (10)$$

Thus, $\mathbf{v}$ is an AWGN if $\mathbf{u}$ is also AWGN. The theoretical BER is

$$\mathrm{BER} = Q\left(\sqrt{\frac{P\sigma_{\mathbf{w}}^2}{\sigma_{\mathbf{x}}^2 + \sigma_{\mathbf{n}}^2}}\right) \text{ with } Q(x) = \int_x^{+\infty} \frac{e^{-\frac{u^2}{2}}}{\sqrt{2\pi}} du \quad (11)$$

3.3. Security

Attacks on the security of a watermarking algorithm aim at estimating the secret key from several documents watermarked with the same key. In the proposed watermarking scheme, the LPTV filter coefficients are kept secret. With the simple implementation based on multiplication by pseudo-random matrices, the principle of the security of LPTV filters is similar to that of DS analysed in [12]. For instance, LL-LPTV filters with $p = 0$ can be considered as a DS formulation in an invertible "transformed domain", the polyphase domain. mod-LPTV filters can as well be considered as a particular case of embedding in the spectral domain. The introduction of delays in relations (6) and (7) would increase the security level.

3.4. Maximum Robustness informed embedding

LISS maximizes the watermark robustness to an AWGN attack of variance $\sigma_{\mathbf{n}}^2$ for a fixed distortion by using the knowledge of **x** at the embedding [3]. Let $\mathcal{S}_l$ denote the pulse positions corresponding to a bit m_l of $\mathbf{m}$. LISS can be applied to watermarking based on LPTV:

$$\mathbf{w} = \mathcal{F}(\alpha\mathbf{b} - \lambda\nu) \text{ where } \nu_{|\mathcal{S}_l} = \frac{1}{P} \sum_{k \in \mathcal{S}_l} \left((\mathcal{F}^{-1}(\mathbf{x}))(k)\right) \quad (12)$$

α and λ are a compromise between embedding distortion, host interference rejection and robustness to attack noise. Derivation of the optimal values of α and λ is similar to the case of DS [3].

3.5. LPTV-based spread transform for quantization techniques

In this section, the SCS quantization watermarking scheme is applied at the output **p** of a spread spectrum filtering of the host document. Instead of a projection on a pseudo-noise in [4], the proposed projection function inspired from the detector of traditional LPTV filters is the mean of P_s samples at the output of the LPTV filter. For a given bit m_l, let divide $\mathcal{S}_l$ into P/P_s sets $\mathcal{S}_l^k$. Then

$$p_k = \frac{1}{P_s} \sum_{n \in \mathcal{S}_l^k} \mathcal{F}^{-1}(\mathbf{x})(n), \qquad k = 1, \dots, \frac{P}{P_s} \quad (13)$$

Let **q** denote the SCS quantization error according to $\mathbf{m}$. The unprojection function is:

$$y_k = x_k - \mathcal{F}(\mathbf{q})(k) \quad \forall k \in \mathcal{S}_l^k \quad (14)$$

If $P_s = P$, LPTV-SCS is inspired from ST-SCS. If $P_s = 1$, LPTV-SCS can be seen as SCS with repetition coding in a "transformed domain". If $1 < P_s < P$, LPTV-SCS relates to quantization of a Subspace projection [13] and vector quantization is possible to deal with the remaining redundancy P/P_s.

4. SPECIFIC FILTERS FOR IMAGE WATERMARKING

While the proposed algorithms of Sections 2 and 3 are suitable for various document types and transformed domains, we focus in Sections 4 and 5 on embedding in the spatial domain of natural images.

4.1. Peano-Hilbert scan

Since LPTV filters are defined on unidimensional signals, a bidimensional scan is necessary for image watermarking. Such space-filling curves have been applied in some contexts where 1D processing is involved, such as chaotic mixing [14]. 2D-interleaving has also been considered to prevent error bursts such as in cropping attacks [15]. However to our knowledge, space-filling curves had not been used to improve robustness to host interference, since most DS-based algorithms decorrelate image samples by a random pulse modulation. A Peano-Hilbert scan, that preserves local correlations between neighboring pixels, will be used in what follows. Inherently 2D processings such as psychovisual masks must be applied before scanning.

4.2. Zero-Insertion LPTV filter (ZI-LPTV)

This section proposes to increase mod-LPTV robustness to the host image noise by imposing a constraint on the decoding inverse LPTV filter matrix A^{-1}. In order to deal with a band-limited signal at the decoding, NRZ coding **b** of the message **m** is used. Let $\mathrm{Int}(n)$ denote the integer part of n. The bandwidth of **b** is $[-\beta, \beta]$, where $\beta = \mathrm{Int}(\frac{T}{P}) + 1$. The only other constraint being the invertibility of A, we propose to totally cancel the contribution of **x** in $[-\beta, \beta]$. With a Peano-Hilbert scan, the spectrum of a natural image is low-pass (cf Fig. 2). Empirically, 99.5% of the power lies in $[-\delta, \delta]$, where $\delta = \frac{1}{16}$. Thus, we impose the following constraint:

$$a^{-1}(\frac{T}{2} + k, \frac{T}{2} + l) = 0 \quad \forall (k, l) \in \{-\delta, \dots, \delta\} \times \{-\beta, \dots, \beta\}$$

The impact of ZI-LPTV is displayed on its bifrequency map [11] (cf Fig. 1), which consists of T parallel impulsive lines corresponding to the modulator filters. The output spectrum of the encoding LPTV filter is still spread on all frequencies, and the filter is still invertible. Fig. 2 displays spectral results of ZI-LPTV for natural image watermarking. Such results could also be obtained with an LTI filter by combining DS with NRZ coding, Peano-Hilbert scanning and low-pass filtering before detection. However, ZI-LPTV achieves perfect invertibility for a watermark spread on all frequencies. It is also more robust to cropping since for large T its impulse response is large.

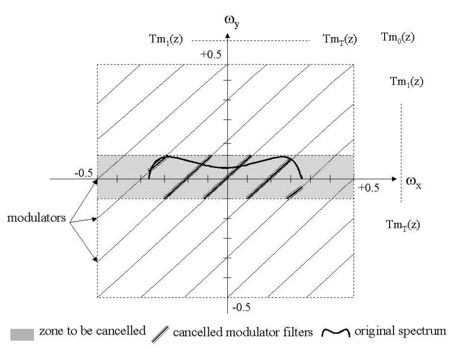

Fig. 1. Cancellation of a frequential band of V for band-limited U

4.3. Spectral masking LPTV filter (mask-LPTV)

Denoising attacks aim at estimating **w** from **y**, in order to remove it. It has been shown that the watermarks that achieve the best robustness to the Wiener filtering attack are those that respect the so-called Power Spectrum Condition (PSC): the spectrum of **w** must be similar to that of **x** [16]. In this section, mod-LPTV is adapted to shape the spectrum of **w** with respect to the PSC. Let $\mathcal{P}_k$ denote the image power in the frequential band $[\frac{k}{T}, \frac{k+1}{T}]$. The power of **w** in this band must be close to that of **x**. The spectrum of the input **b** is supposed to be white, by using repetition coding and/or pre-whitening of **m**. The following constraint is imposed on a pseudo-random matrix A:

$$\sum_{l=1}^{T} a(k, l) = \mathcal{P}_k$$

A is still invertible, but not orthogonal. Since **w** is now low-pass, blind embedding leads to a great sensibility of the decoding to the host noise. Thus, mask-LPTV must be combined with pre-whitening at the detector and/or host interference pre-cancellation (cf section 3.4). Moreover, since the spectrum of **x** is concentrated on a small band, a fine piecewise constant approximation is achieved only for a large T, which increases the computational cost. A piecewise linear weighting could also be used in a second step.

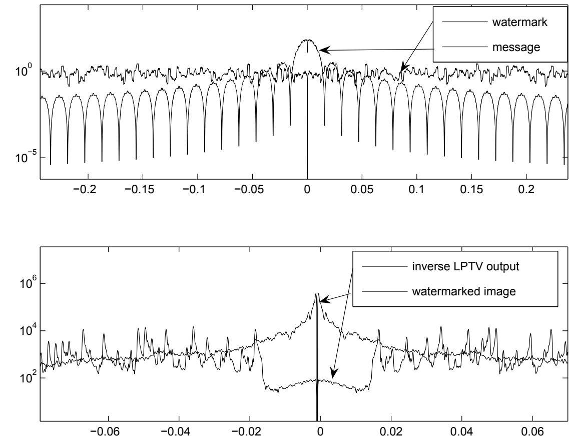

Fig. 2. Embedding (top) and decoding (bottom), ZI-LPTV, DWR=38 dB, $L = 4096$, $T = 512$

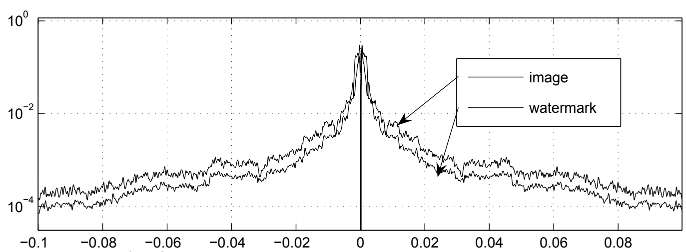

Fig. 3. Output spectrum of mask-LPTV, $T = 512$

5. ROBUSTNESS

In this section, we compare the performance of the proposed techniques to PCCs combined with a Peano scan, and to the classical algorithms DS, LISS and ST-SCS. Small periods T are used for computational reasons only. DWR=38 dB controls the embedding distortion. LPTV filters can be combined with all psychovisual masks designed for DS techniques, without penalizing the decoding. Objective perceptual distances have shown similar performance of LPTV filters and DS when a psychovisual mask is used.

Fig. 4 shows that the performance of LPTV filters on natural images is very different from the theoretical one under the AWGN hypothesis. Indeed, repetition coding, Peano scanning and the periodicity of LPTV filters impose that correlated blocks of pixels contribute to differing pulse position sets $\mathcal{S}_l$. The BER of LPTV filters is strongly dependent on L, but always outperforms DS. ZI-LPTV diminishes the contribution of the host noise variance. LPTV filters are also more robust to attacks such as JPEG compression (cf Fig. 5). Fig. 6 shows that the lower host noise variance contribution in the derivation of λ benefits to the performance of improved LPTV filters when L is large. Fig. 7 shows that LPTV filters are an appropriate spread transform for quantization-based watermarking schemes.

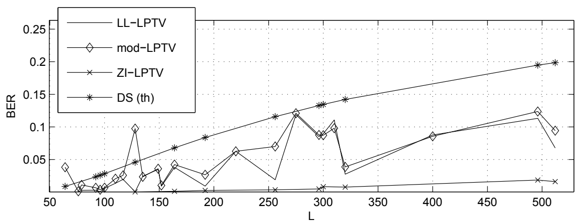

Fig. 4. Influence of the message rate L, DWR=38dB

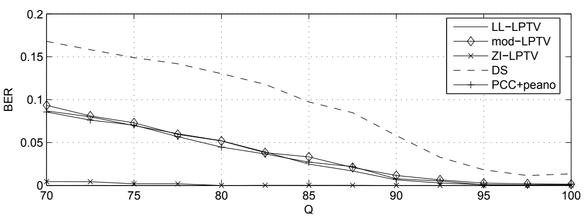

Fig. 5. Robustness to JPEG compression, DWR=35 dB, $L = 100$

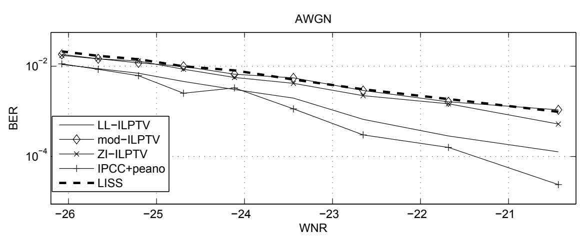

Fig. 6. Robustness to AWGN, Maximum Robustness strategy, DWR=38dB, L=100

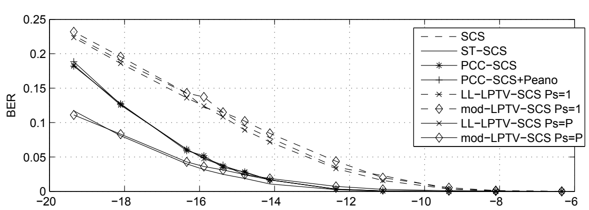

Fig. 7. Robustness to AWGN, Quantization based techniques, DWR=38 dB, $L = 1300$

6. CONCLUSION

In this paper, LPTV filters have been applied to digital watermarking. LPTV belong to the classical framework of modulation and transmission in a noisy channel and are closely related to classical spread spectrum schemes. They are a convenient theoretical and practical tool that combines spectrum spreading, spatial interleaving and spectral shaping. Due to the non-stationarity of natural images, LPTV filters combined with repetition coding and a Peano-Hilbert scan have shown a better robustness to natural host image noise than classical DS techniques, according to simulations. Extensions to improved spread spectrum and spread transform quantization watermarking techniques have been proposed. LPTV filters could also be easily applied to known host-statistics watermarking techniques. Moreover, LPTV filters allow for constraining the output spectrum simultaneously to spreading. Specific LPTV filters have been designed for image watermarking, in order to satisfy the Power Spectrum Condition on the watermark or to eliminate the contribution of low-pass frequencies of a host image. We have focused in this paper on simple implementations based on multiplication by pseudo-random orthogonal matrices. However, the proposed algorithms can be easily adapted to the construction of potentially more powerful and secure LPTV filters by introducing delays. Finally, the use of the cyclostationarity at the output of an LPTV filter is under investigation in a watermarking context.

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