

Multiple Watermarking: A Vector Space Projections Approach

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ABSTRACT

We present a new paradigm for the insertion of multiple watermarks in images. Instead of an explicitly defined embedding process, the watermark embedding is achieved implicitly by determining a feasible image meeting multiple desired constraints. The constraints are designed to ensure that the watermarked image is visually indistinguishable from the original and produces a positive detection result when subjected to detectors for the individual watermarks even in the presence of signal processing operations, particularly compression. We develop useful mathematical definitions of constraint sets for different visual models, for transform domain compression, and for both spread-spectrum and quantization index modulation (QIM) watermark detection scenarios. Using the constraints with a generalized vector space projections method (VSPM), we determine a watermarked signal. Experimental results demonstrate the flexibility and usefulness of the presented methodology in addressing multiple watermarking scenarios while providing implicit shaping of the watermark power to meet visual requirements.

Keywords: Multiple watermarking, vector space projections method (VSPM), set theoretic watermarking, adaptive watermarking, projections onto convex sets (POCS), spread spectrum watermarking, QIM watermarking

1. INTRODUCTION

The widespread use of digital networks for the communication of multimedia data has resulted in a recent spurt of research on techniques for digital watermarking. These methods embed an auxiliary signal in host signal without impacting its functionality and can address a number of applications ranging from authentication, tamper detection, broadcast monitoring, transparent meta-data tagging, and copyright enforcement. In order to address the differing requirements of these various applications, a variety of methods have also been proposed for watermark embedding.

Practical applications often require the use of multiple watermarks for different purposes embedded with different techniques. For instance, in electronic distribution of multi-media content it would be natural to embed one watermark that establishes ownership and another that carries a fingerprint identifying the purchasing party (for the purposes of tracing sources of unauthorized copies). Typical watermarks proposed in the literature utilize ad hoc mechanisms for watermark insertion. The majority of methods also do not address multiple watermarking scenarios which introduce significant new challenges. First of all, the distortion introduced as a result of the combined impact of all watermarks should be imperceptible, a property that is not ensured by the invisibility of watermarks individually. Secondly, each watermark presents potential interference in the detection of other watermarks - which is again not comprehended in the insertion process. These concerns have received some attention in the literature where heuristics have been proposed for the multiple watermarking scenario.¹⁻⁵ These, however, either do not fully account for the joint effect of watermarks,^{1,2} or embed different watermarks in disjoint signal regions/transform coefficients³ to eliminate inter-watermark interference, sacrificing capacity in the process.¹

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In this paper, we offer a method for inserting multiple watermarks into the same image using a vector-space projection (VSP) framework. The multiple watermarking problem is posed differently from formulations proposed in the past. Instead of defining ad hoc insertion techniques and rules, we define the detection processes for the individual watermarks and determine the watermarked image so as to simultaneously satisfy the (multiple) watermark detection requirements. In the same framework, the combined visual impact of multiple watermarks is directly accounted for through the use of suitable visual models. Inter-watermark interference is also comprehended in the watermark embedding process as is robustness to compression. A watermarked image is determined to simultaneously satisfy all these requirements using a VSP method (VSPM) for estimating a feasible point subject to the multiple constraints. We illustrate the effectiveness of the methodology by simultaneously inserting spread-spectrum (SS), quantization index modulation (QIM) and lowest-significant-bit (LSB) watermarks in a cover image. The LSB watermark* is fragile, whereas the SS and QIM watermarks are robust to JPEG compression.

General VSP methods can suffer from problems with convergence. If the constraints are all convex with readily computable projection operators, the iterative method of projections onto convex sets (POCS) guarantees convergence to a feasible solution (if one exists). For our formulation, we find that all sets other than robustness to compression are convex. In order to incorporate robustness to compression, we propose both a convex approximation to the constraint and a general heuristic VSP method for watermark embedding. We experimentally illustrate the performance of both the approximation set and the heuristic modification.

2. CONSTRAINTS FOR MULTIPLE WATERMARKING

In this section, we formulate multiple watermarking as a feasible point estimation problem. We define constraints imposed on the watermarked signal by:

- the detectors for the embedded watermarks,
- the requirement of visual fidelity to the original image, and
- the required resilience to compression.

A watermarked image can be determined by estimating a feasible point that satisfies all these constraints. This is conceptually illustrated in Fig 1 where the signal space is represented in two-dimensions. The half-planes labeled S_1^1 , S_1^2 represent signal regions that meet corresponding spread-spectrum watermark detection constraints, S_2^1 represents the signal region corresponding to a quantization index modulation (QIM) watermark detection constraint and the region S_4 represents the region that meets a desired visual fidelity constraint. Thus the region corresponding to the intersection of all of these sets meets the multiple watermark requirements along with the visual fidelity requirement. A watermarked image may be estimated by determining a *feasible* signal that lies in this intersection. Note that the graphical representation is for the purpose of illustration only - in actual practice, the signal space has much higher dimensionality.

Next we consider the representation of each of the constraints as a set corresponding to the feasible region of the signal space over which the constraint is satisfied. With a view to using these constraints in a VSP framework, we also consider the convexity of these sets and convex approximations to the sets when the sets are non-convex. VSP and POCS (using approximations) methods for watermarking based on these constraint sets are then described in Section 3.

2.1. Detectability and robustness of multiple spread spectrum watermarks

Spread spectrum (SS) embedding⁶ is a commonly used watermark insertion method. In the simplest SS embedding scenario, a key-dependent pseudo-random spread spectrum signal is added to the cover image (or transform coefficients). At the receiver, the presence or absence of this signal is detected by regenerating the same key-dependent pseudo random signal, correlating with the received image, and comparing the computed correlation

*The LSB watermark may be considered a special case of QIM embedding.

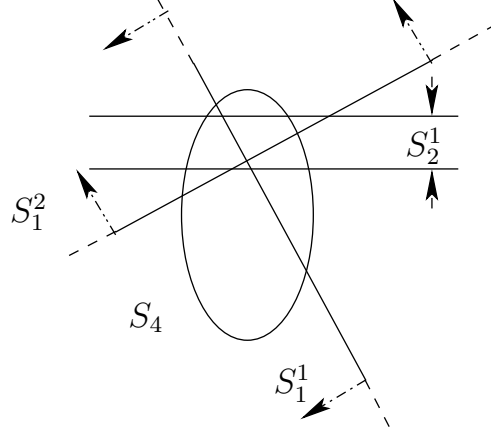


Figure 1. Multiple watermark embedding as a feasible point estimation problem.

against a pre-determined threshold. The signal is deemed present if the correlation exceeds the threshold and absent otherwise. Since the pseudo-random signal spreads the energy of the embedded signal over a wide frequency range, the technique offers robustness against several attack modifications even under the small embedding power requirements that are mandated by visibility constraints. The method is readily generalized to carry arbitrary message bits as watermark information. For simplicity, however, here we describe only the scenario where the presence or absence of a spread-spectrum “watermark signal” is detected [†].

In the VSP framework, the spread spectrum watermark is implicitly embedded by imposing a constraint on the resulting image for exceeding a minimum embedding strength⁷ as measured by a correlation detector. Note that the VSP framework imposes constraints on the final watermarked image and thus automatically accounts for inter-watermark interference even though the watermarks share the same spatial support.

For the detection of spread-spectrum watermarks, we consider the mean-corrected correlation detector.⁸ If we have K watermarks $\{\mathbf{w}_j\}_{j=0}^{K-1}$ that are to be embedded in the same image, there are K corresponding constraint sets that require that the corresponding correlation values exceed pre-determined thresholds [‡].

$$\mathbb{S}_1^j \equiv \{\mathbf{x} : (\mathbf{w}_0 - \bar{\mathbf{w}}_0)(\mathbf{x} - \bar{\mathbf{x}}) \geq \tau_j\}, \quad j = 1, \dots, K. \quad (1)$$

$$\equiv \{\mathbf{x} : \mathbf{w}^T(\mathbf{x} - \bar{\mathbf{x}}) \geq \tau_j\}, \quad j = 1, \dots, K. \quad (2)$$

where $\mathbf{w} = \mathbf{w}_0 - \bar{\mathbf{w}}_0$ and $\bar{\mathbf{z}}$ represents a vector of the same size as \mathbf{z} and having each of its elements as the sample mean of the vector \mathbf{z} . The constraint on each watermark embedding strength is formulated by imposing a minimal value τ for the correlation. If $\mathbf{X} \in \mathbb{R}^{R \times S}$ denotes the image with dimensions $R \times S$ and $\mathbf{W} \in \mathbb{R}^{R \times S}$ denotes the pseudo-noise watermark sequence, we denote $\mathbf{x} = \text{vec}(\mathbf{X}) \in \mathbb{R}^{RS}$ and $\mathbf{w} = \text{vec}(\mathbf{W}) \in \mathbb{R}^{RS}$ as the vectors obtained by stacking together the columns of each. We will adopt the notation in terms of 1-dimensional vectors throughout and assume that any image operators are also represented as matrices/functions conformal with the vector representation. The set defined above is readily seen to be convex.

It is worth noting that VSP framework automatically accounts for any watermark-cover interference as well as inter-watermark interference. All constraints in (2) are simultaneously imposed on the watermarked image.

[†]In the context of this scenario, information bits may be embedded (for example) by using antipodal signals w and $-w$ to embed a value of 0 and 1, respectively. This results in a ternary detection process corresponding to a detector response of 0, 1, or no-embedding.

[‡]The presence of additional noise sources in the channel suggests that the thresholds used at the embedder be higher than those at the detector. This may be formally established by a desired confidence interval for detection in the presence of noise.⁹

The formulation is suitable for either simultaneous or sequential watermark detection of at the receiver provided embedding is performed simultaneously, i.e., all keys are available concurrently during the embedding process.

2.2. Detectability and robustness of multiple QIM Watermarks

Quantization index modulation (QIM)¹⁰ watermarking offers a high capacity embedding method (for a given distortion level). We consider a version of QIM embedding¹¹ in which each bit is embedded[§] by using a subtractive-dither scalar-quantizer on the mean of L randomly selected locations within the image. Thus if the sample values at the L randomly selected sample location in the original image are denoted by a sample vector \mathbf{y}_0 , the mean of these values is $\mu_i = \frac{1}{L} \mathbf{1}^T \mathbf{y}_0$, where $\mathbf{1}$ is a $L \times 1$ vector of 1's. The watermarked image carries a bit value b if

$$\frac{1}{L} \mathbf{1}^T \mathbf{y} = Q(\mu_i + d_i + b\Delta, \Delta) - d_i \equiv \mu_i^{q,b} \quad (3)$$

where \mathbf{y} is the vector of sample values in the watermarked image at the chosen L locations, Q is the integer scalar quantizer with Δ as scaling parameter and d_i is pseudo-random scalar dither which is assumed iid uniformly-distributed between $-\Delta/2$ and $\Delta/2$. Note that this is similar to the spread-transform dither modulation¹⁰ and to the method of "quantizing randomized semi-global image statistics".¹²

For the VSP framework, the quantization based detectability set is then given by¹¹:

$$\mathbb{S}_2^i \equiv \{\mathbf{x} : \frac{1}{L} \mathbf{1}^T \mathbf{y}_i = \mu_i^{q,b_i}\} \quad i = 1, \dots, M \quad (4)$$

where N denotes the number of bits embedded with values $\{b_i\}_{i=1}^N$, \mathbf{y}_i denotes the $L \times 1$ vector of sample values at the L random locations selected for embedding of the i^{th} bit, and other terms are as before. Note that the random locations selected for embedding of different bits need not be disjoint. The sets in (4) are readily seen to be convex sets.

The definition of (4) assumes watermark embedding in the spatial domain. The method, however, is generic in nature and can be applied to most transform domains which may have possible attractive properties. For any linear transform domain, convexity of the set is preserved.

2.3. LSB Watermark Constraints

LSB modulation is one of the simplest techniques for embedding information in a multimedia signal. The information is embedded by replacing the LSBs of the pixel values within the image with the desired message bits. Since the distortion introduced through the modification of LSBs is quite low, LSB modulation is normally invisible. LSB plane watermarks are normally fragile and lost under most signal processing operations. LSB watermarks are however useful for image authentication applications.^{13,14}

An LSB watermark may readily be incorporated in the VSP framework by defining a constraint set that constrains the image LSB values to the desired message bits:

$$\mathbb{S}_3 \equiv \{\mathbf{x} : LSB(\mathbf{x}) = \mathbf{T}\} \quad (5)$$

where \mathbf{T} is the image size bit-plane carrying the information to be embedded, and $LSB(\mathbf{x})$ refers to the operation of retrieving least significant bit plane of the image. Note that the set in (5) is in fact a special case of QIM embedding and can be expressed in the form used in Section 2.2. It follows that the set is convex.

[§]Even though our method does not explicitly embed the watermark, for the purpose of clearly describing the motivation for our constraint sets we choose to ignore this distinction in our description.

2.4. Contrast Sensitivity Visual Constraint

Low frequency distortion introduced by watermark signal is more visible compared to high frequency distortion. This behavior of human visual system in monochrome images can be approximately modeled by a linear shift invariant 2-D filter.¹⁵ The difference between perceived original image $\mathbf{H}\mathbf{x}_0$ (where \mathbf{x}_0 denotes the original image) and perceived watermarked image $\mathbf{H}\mathbf{x}$ should be kept low during embedding. Euclidean distance gives a suitable norm for quantifying the difference:

$$\mathbb{S}_4 \equiv \{\mathbf{x} : \|\mathbf{H}\mathbf{x} - \mathbf{H}\mathbf{x}_0\| \leq \beta\} \quad (6)$$

where $\|v\|$ represents the Euclidean norm of v and β is a suitably chosen threshold.

For the model, the spatial filter H is represented in the frequency domain by a radially isotropic function $H(f_r) = 2.6[0.0192 + 0.114f_r]e^{-(0.114f_r)^{1.1}}$ where f_r denotes the radial frequency in cycles per degree.¹⁵

2.5. Spatial Masking Visual Constraint

The contrast sensitivity model does not account for localized perturbations of the image in a small region. We use an additional "spatial masking" model to limit perturbations to ensure that the local variations are imperceptible. Our model exploits the perceptual phenomenon of spatial masking¹⁶ in which perturbations introduced in an image region at a frequency are masked by stronger image content at similar frequencies. Particularly, we employ spatial domain texture model proposed by Pereira et al.¹⁷ The model provides pixel-wise upper and lower bounds for the difference from the original image. The resulting constraint can be expressed as:

$$\mathbb{S}_5 \equiv \{\mathbf{x} : \mathbf{l} \leq \mathbf{x} \leq \mathbf{u}\} \quad (7)$$

where \mathbf{u} and \mathbf{l} form pixel-wise upper and lower bounds respectively.

2.6. Robustness to compression constraint for spread spectrum watermarks

In some watermarking applications, robustness against content preserving signal processing is desirable. Here, we concentrate on a common type of non-malicious signal processing operations: lossy compression, specifically JPEG compression. JPEG compression is performed by quantization of DCT coefficients of an image at a predetermined rate based on the desired image quality. The spread spectrum watermark is robust against compression if the detector response is above threshold after compression. The set of images illustrates this kind of robustness can be formulated as:

$$\mathbb{S}_6 \equiv \{\mathbf{x} : w^T(IDCT(Q[DCT(\mathbf{x})]) - \overline{IDCT(Q[DCT(\mathbf{x})])}) \geq \gamma\} \quad (8)$$

where $Q[\]$ denotes the quantizer, DCT represents the discrete transform operation from the spatial domain into the transform domain, and IDCT represents the inverse discrete cosine transform. The quantizer $Q[\]$ then consists of the 64 quantizers for the DCT coefficients within each 8×8 block of DCT coefficients (where the frequency dependent scaling factor is included as part of the quantizer). The constraint of (8) is usually not convex. Motivated by the observation that typical transform coding schemes provide coding gain through the compaction of signal energy into a few coefficients, we approximate the set (8) by the following set⁷:

$$\hat{\mathbb{S}}_6 \equiv \{\mathbf{x} : w^T(IDCT(Q_0[DCT(\mathbf{x})]) - \overline{IDCT(Q_0[DCT(\mathbf{x})])}) \geq \gamma\} \quad (9)$$

where $Q_0[\]$ refers to the "quantizer" determined from the original image X_0 by defining its constituent scalar quantizers as

$$Q_0^k[t] = \begin{cases} 0 & Q^k[(DCT(\mathbf{x}_0))_k] = 0 \\ t & \text{otherwise} \end{cases} ; \quad k = 0, 1, \dots, RS - 1. \quad (10)$$

where $(DCT(\mathbf{x}_0))_k$ denotes the k^{th} transform coefficient of the original image \mathbf{x}_0 . Thus the quantizer $Q_0[\]$ sets the transform coefficients that are zero in $Q[DCT(\mathbf{x}_0)]$ to zero and leaves other coefficients unchanged. This approximation has the underlying assumption that the transform coefficients that is quantized to zero cause the major loss of watermark information.

2.7. Robustness to compression constraint of QIM watermarks

Using the same motivation described above, the robustness to compression requirement for QIM watermarks may be approximated by[¶]:

$$\widehat{S}_7^i \equiv \{\mathbf{x} : \overline{\mathbf{S}_i(IDCT(Q_0[DCT(\mathbf{x})]))} = \mu_i^q\} \quad (11)$$

where \mathbf{S}_i represents the $L \times RS$ vector that extracts the pseudo-random locations for the i^{th} QIM watermark, i.e. $\mathbf{y}_i = \mathbf{S}_i\mathbf{x}$, overline refers to mean of the variable and $Q_0[\]$ refers to the “quantizer” determined from the original image \mathbf{x}_0 by defining its constituent scalar quantizers as

$$Q_0^k[t] = \begin{cases} 0 & Q^k[(DCT(\mathbf{x}_0))_k] = 0 \\ t & \text{otherwise} \end{cases} ; \quad k = 0, 1, \dots, RS - 1. \quad (12)$$

3. VECTOR SPACE PROJECTIONS METHOD FOR WATERMARKING

VSPM finds a point in a vector space that lies within intersection of a number of constraint sets. The method works by selecting an initial point in the vector space and projects successively on to the collection of constraint sets to generate the next iterate. The projection operation consists of finding the nearest point in the constraint set to the current point. The order of the constraint sets in the collection may be arbitrarily chosen. Ideally, the iterates generated by this process converge to a *feasible* point that satisfies all the constraints. In general convergence is not guaranteed, though it may be empirically seen for well selected initial points. If all constraint sets are convex and closed then VSPM reduces to the method of POCS, which is globally convergent provided the sets have a non-empty intersection.

We insert robust SS, relatively less robust QIM and fragile LSB watermarks into the same image using the VSP method. The sets defined in Section 2 are used for embedding. We first present the case where non-convex constraints are replaced by their convex approximates as described in Section 2, yielding a POCS algorithm for multiple watermarking and then present the general VSPM using an alternate heuristic for incorporating robustness to compression. Details of required projection operators for the sets may be found in related work.^{7, 11}

3.1. Multiple Watermarking by POCS

POCS Algorithm statement:

1. Initialize set $k = 0$ and initial image as \mathbf{x}_0 .
2. Project sequentially onto convex constraint sets: $\{S_1^j\}_{j=1}^K, \{S_1^i\}_{i=2}^M, S_3, S_4, S_5, \widehat{S}_6, \widehat{S}_7 \quad \forall i, j$ to obtain the next iterate.

$$\mathbf{x}_{k+1} = (P_{\widehat{S}_7}(P_{\widehat{S}_6} \dots P_{S_2^I}(P_{S_1^J}(\mathbf{x}_k) \dots))), \quad k = 0, 1, \dots \quad (13)$$

where

$$P_{S_1^J}(\mathbf{u}) = (P_{S_1^N}(P_{S_1^{N-1}} \dots P_{S_1^2}(P_{S_1^1}(\mathbf{u}) \dots))), \quad (14)$$

$$P_{S_2^I}(\mathbf{v}) = (P_{S_2^K}(P_{S_2^{K-1}} \dots P_{S_2^2}(P_{S_2^1}(\mathbf{v}) \dots))), \quad (15)$$

and

$$\begin{aligned} P_S(Y) &= \text{Projection of } Y \text{ onto } S \\ &= \arg \min_{Z \in S} \|Z - Y\| \end{aligned} \quad (16)$$

[¶]Once again this may be developed in a more generalized and formal framework.⁹

3. Check for convergence, i.e. check if

$$\| \mathbf{x}_{k+1} - \mathbf{x}_k \| < \varepsilon$$

and,

$$\mathbf{x}_{k+1} \in \left(\bigcap_i S_1^i \right) \cap \left(\bigcap_i S_2^i \right) \cap S_3 \cap S_4 \cap S_5 \cap \hat{S}_6 \cap \hat{S}_7$$

if converged set watermarked image \mathbf{x}_{k+1} and terminate iterations else set $k \leftarrow k + 1$ got to 2.

3.2. Multiple Watermarking by a General VSPM

Instead of the convex approximation for incorporating robustness to compression, here we consider an alternate heuristic that selects among all possible JPEG quantized images (at a given quality factor) an image that satisfies the desired watermarking constraints. The set of JPEG quantized images may be incorporated within the VSPM framework by defining the set

$$S_8 = \{ \mathbf{x} \mid \mathbf{x} = IDCT(Q[DCT(\mathbf{x})]) \} \quad (17)$$

Note that the set S_8 is in fact a discrete set and its elements are all the possible JPEG quantized images. The projection onto this set is simply accomplished by JPEG compressing the image.

1. Initialize set $k = 0$ and initial image as \mathbf{x}_0 .
2. Project onto the set S_8 by JPEG compressing the image with the a quality factor determined by desired level of compression robustness.

$$\mathbf{t}_k = P_{S_8}(\mathbf{x}_k)$$

3. Project resulting image sequentially onto convex constraint sets: $\{S_1^j\}_{j=1}^K, \{S_2^i\}_{i=1}^M, S_3, S_4, S_5 \quad \forall i, j$.

$$\mathbf{x}_{k+1} = (P_{S_5}(P_{S_4}(P_{S_3}(P_{S_2^I}(P_{S_1^J}(\mathbf{t}_k))))), \quad k = 0, 1, \dots \quad (18)$$

4. Check for convergence, i.e. check if $\| \lambda_{k+1} - \lambda_k \| < \varepsilon$ and $0 < \lambda_{k+1} < \sigma$ for each projection. Note that λ_k refers to the Lagrange multiplier parameter for the constrained optimization problem corresponding to each of the convex set projections.⁷ If the convergence criterion is satisfied, the watermarked image is set to \mathbf{x}_{k+1} and the algorithm terminates, otherwise we set $k \leftarrow k + 1$ and go to 2.

Note that since S_8 is non-convex (in fact it is discrete), the VSP method is not guaranteed to converge. For situations, where the iterations get stuck in a repeating pattern without convergence, as a heuristic modification we increase the Lagrange parameters by ρ for the watermark detectability constraints. The resulting “projections” have the same direction as the constrained problem, but the projection is to a point inside the detectability set rather than the boundary of it. This update procedure helps the algorithm get out of local non-convergent regions.

4. EXPERIMENTAL RESULTS

We insert multiple watermarks into gray scale images by VSP. In the first case, we consider the POCS method where the non-convex sets are replaced by convex approximations and in the second case we consider the heuristic VSPM outlined above. We used the *Goldhill*, *Lena*, *Barbara*, *Mandrill*, *Washsat*, *Peppers*, *Boat*, *Zelda* images from USC test image set¹⁸. These are 8-bit gray-scale images with a of size 512×512 pixels.

The parameters of the algorithm are chosen as follows: The bound for the overall image fidelity threshold¹⁵ is set at $\beta = 10$ and values of $P_0 = 30$ and $P_1 = 3$ are used for the pixel-wise image fidelity parameters.¹⁷ The embedding strength is set to the linear correlation lower-bound of $\tau_j = 1.0 \times RS$, corresponding to a normalized value of $\bar{\tau} = \frac{\tau_j}{RS} = 1.0$. The corresponding detection threshold at the receiver is set to $\tau_r = 0.6$. The Q factor we choose to determine the DCT coefficients close to zero is 70.

4.1. Joint SS-QIM-LSB Watermark Embedding By POCS

4.1.1. Detection Performance

Watermark embedding by POCS eliminates all inter-watermark interference as well as interference between watermark and cover file. Due to this fact, the resulting image shows superior performance in detection process. Table 1 illustrates the correctly received watermarks after embedding^{||}. The interference among watermarks is managed successfully so that we do not observe any bit error rates.

A useful property of POCS embedding is that potential inter-watermark interference and interference with the cover are detected during embedding. If one or more watermark constraints cannot be satisfied in the POCS iterations, the capacity of the embedding can be reduced or visual fidelity can be sacrificed for accomplishing the embedding.

	# Embedded	# Correctly Recovered
<i>SS</i>	40	40
<i>QIM</i>	500	500
<i>LSB</i>	262144	262144

Table 1. Detection of multiple watermarks of different types from Goldhill image.

4.1.2. Visual Adaptation

The visual models employed during embedding process ensure invisibility of the watermark signal in the image. The impact of the watermarked image is illustrated on Goldhill image (see Fig. 2). Fig. 2(a) shows the original image and Fig. 2(b) illustrates the multiple watermarked image obtained by POCS. One can see that despite the multiple watermarks embedded the visual fidelity of the watermarked image to the original is quite high.



Figure 2. (a) Original Goldhill image.(b) Goldhill image jointly watermarked by SS-QIM-LSB (40 bits, 500 bits, 262144 bits).

^{||}As remarked earlier, for SS embedding the detection distinguishes between the presence and absence of watermarks and for QIM embedding the detection estimates an embedded bit value.

For a better appreciation of visual fidelity constraints, we performed the multiple watermark embedding using POCS while excluding the visual constraints. Fig. 3 shows the image obtained without visual constraints. The watermark noise is visible in many regions and the adaptation performance of watermark noise onto the image is poor compared to the watermarked image illustrated in fig 2(b). Here note that all other parameters, such as robustness to compression and successful detectability of the watermark bits is kept unchanged compared to the experiments that yield Fig 2(b).



Figure 3. Goldhill image jointly watermarked by SS-QIM-LSB (40 bits, 500 bits, 262144 bits) without visual constraints.

4.1.3. Robustness To Compression

We report the robustness of the combined multiple watermarks to compression. Table 2 summarizes the results for watermark detection for the proposed scheme across the 8 images from the USC image set for JPEG compression with Q-factors ranging from 90 down through 10. Each entry in the table is represented as a/b where b is the total number of bits embedded in the experiment and a is the number of these blocks in which the watermark is successfully detected (for the corresponding compression level).

	$Q = 90$	$Q = 80$	$Q = 70$	$Q = 60$	$Q = 50$	$Q = 40$	$Q = 30$	$Q = 20$
<i>SS</i>	320/320	320/320	248/320	51/320	0/320	0/320	0/320	0/320
<i>QIM</i>	4000/4000	4000/4000	3972/4000	3221/4000	3001/4000	2953/4000	2612/4000	2214/4000

Table 2. Detection of multiple watermarks under various JPEG compression levels .

We perform our experiments without the convex approximations of the robustness to compression sets \hat{S}_6, \hat{S}_7 to illustrate the effectiveness of these sets. Table 3 summarizes the detection results when the watermarks are inserted without robustness to compression constraints. Compared to the robustness achieved at Table 2, the watermarks are lost at mild compression levels in Table 3.

4.2. Joint SS-QIM-LSB Watermark Embedding By VSPM

The parameters ρ and σ are both chosen to be 0.05. The quality factor employed in JPEG compression is 80.

	$Q = 90$	$Q = 80$	$Q = 70$	$Q = 60$	$Q = 50$	$Q = 40$	$Q = 30$	$Q = 20$
<i>SS</i>	320/320	320/320	5/320	0/320	0/320	0/320	0/320	0/320
<i>QIM</i>	4000/4000	3948/4000	2881/4000	2633/4000	2548/4000	2424/4000	2347/4000	1994/4000

Table 3. Detection of different watermarks when watermarks are inserted without robustness to compression sets.

4.2.1. Detection Performance

Watermark embedding by the proposed VSPM algorithm results in detection of watermarks as tabulated in Table 4. As the table reveals, the superior capability of the method to handle interference remains similar to the POCS method. However, employing the heuristically motivated compression constraint has caused a significant decrement in capacity. This is due to the fact that, in VSPM scheme, we are highly constrained by the JPEG compression set, limited to a selection from the set of images that match their JPEG compressed representation (at the Q-factor used for set S_8 while embedding).

	# Embedded	# Correctly Recovered
<i>SS</i>	4	4
<i>QIM</i>	10	10
<i>LSB</i>	262144	262144

Table 4. Detection of various multiple watermarks on Goldhill image.

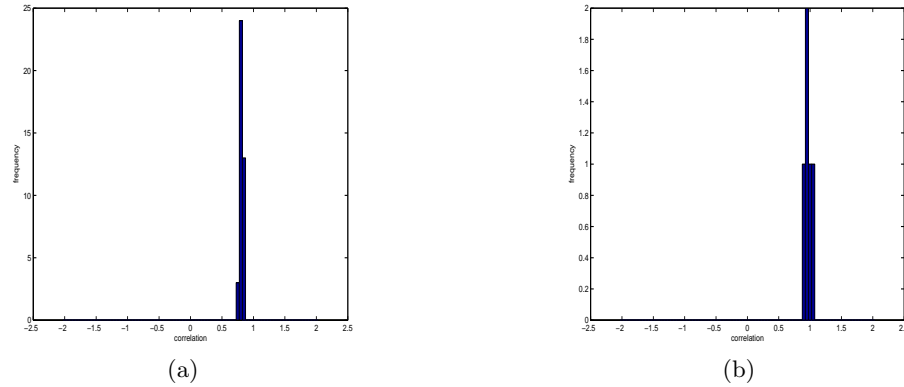


Figure 4. (a) Histogram of detector values when POCS watermarked image is compressed by Q=80.(b) Histogram of detector values when VSPM watermarked image is compressed by Q=80.

4.2.2. Robustness To Compression Performance

We report the robustness of the combined multiple watermarks to compression. Table 2 summarizes the results for watermark detection for the proposed VSPM scheme across the 8 images from the USC image set for JPEG compression with Q-factors ranging from 90 down through 10.

The difference between the convex approximation of the robustness to compression set and the heuristic VSPM modification can be seen in the detection performance of the embedded SS watermarks shown in Fig. 4. and Fig.4(b). Due to the nature of JPEG compression, the VSP method assures that for compression quality factors higher than the factor used for embedding, the image remains unchanged and therefore the watermark power remains at the threshold τ used in embedding. This can be seen in Fig. 4. The same property is not assured for the embedding performed by using the approximation to the robustness to compression set.

The robustness of the combined multiple watermarks to compression when JPEG compression is not included in the algorithm is reported in Table 6. Some of SS and QIM watermarks are undetected at Q=70.

	$Q = 90$	$Q = 80$	$Q = 70$	$Q = 60$	$Q = 50$	$Q = 40$	$Q = 30$	$Q = 20$	$Q = 10$
<i>SS</i>	32/32	32/32	32/32	32/32	16/32	0/32	0/32	0/32	0/32
<i>QIM</i>	80/80	80/80	80/80	80/80	75/80	72/80	53/80	44/80	36/80

Table 5. Detection of multiple watermarks at various JPEG compression levels .

	$Q = 90$	$Q = 80$	$Q = 70$	$Q = 60$	$Q = 50$	$Q = 40$	$Q = 30$	$Q = 20$	$Q = 10$
<i>SS</i>	32/32	32/32	0/32	0/32	0/32	0/32	0/32	0/32	0/32
<i>QIM</i>	75/80	69/80	57/80	49/80	44/80	39/80	41/80	35/80	36/80

Table 6. Detection of multiple watermarks at various JPEG compression levels without employing JPEG compression .

5. CONCLUSION

We present a vector space projection (VSP) approach for multiple watermarking wherein a number of watermarks of different types are embedded in a cover signal. The approach provides a structured method for simultaneously satisfying detectability requirements for each of the watermarks while providing the required perceptual fidelity with respect to the cover. We showed that the framework can incorporate watermarks of both spread-spectrum and quantization index modulation varieties, visual fidelity constraints arising from both texture masking models and contrast sensitivity, and watermark robustness to JPEG compression. Using convex approximations to the non-convex constraints, we indicated how the VSP method can be reduced to a globally convergent projections onto convex sets (POCS) method.

Experimental results demonstrate the effectiveness of both the VSP and POCS versions of the algorithms for addressing multiple watermarking. The results show that the methods automatically and implicitly distribute the embedding power available under distortion constraints across the multiple watermarks as well as over spatial and frequency domain supports in order to meet detectability, perceptibility, and robustness to compression constraints. The VSP approach therefore provides a particularly effective method for multiple watermarking.

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